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RESPONSES OF SAGINAW BAY, LAKE HURON, TO REDUCTIONS IN PHOSPHORUS LOADINGS FROM THE SAGINAW RIVER

by

Victor J. Bierman, Jr.
and
David M. Dolan
Large Lakes Research Station
U.S. Environmental Protection Agency
9311 Groh Road
Grosse Ile, Michigan 48138

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16. ABSTRACT

The purpose of this report is to present results of phosphorus load reduction simulations based on refinements to the state of the art of mathematical modeling research on Saginaw Bay. These refinements were developed subsequent to the Task Group III, a bilateral technical group to review phosphorus loadings (Vallentyne and Thomas 1978). One objective is to provide additional information to the International Joint Commission (IJC), the State of Michigan, and other appropriate planning agencies for evaluating the scientific credibility and the degree of accuracy of the WQA loading objective for Saginaw Bay. Another objective is to document these predictive results prior to a comprehensive re-survey of Saginaw Bay being conducted in 1980.

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INTRODUCTION

Saginaw Bay is an important component of the Lake Huron system and is one of the most highly enriched major basins in the Great Lakes. The bay has been identified as one of 44 Great Lakes "Problem Areas" (Great Lakes Water Quality Fifth Annual Report - Appendix B, 1977). Under terms of the 1978 Water Quality Agreement (WQA) between Canada and the United States, a substantial reduction will be required in phosphorous loadings to the bay to meet the desired water quality objectives.

As part of the 1978 WQA, phosphorus loading objectives were established for each of the major basins in the Great Lakes. These objectives were based on the recommendations of Task Group III, a bilateral technical group to review phosphorus loadings (Vallentyne and Thomas 1978). Results of phosphorus load reduction simulations from five different mathematical models were used to relate phosphorus loads to in-lake responses in terms of appropriate water quality parameters.

The purpose of this report is to present results of phosphorus load reduction simulations based on refinements to the state of the art of mathematical modeling research on Saginaw Bay. These refinements were developed subsequent to the Task Group (TG) report. One objective is to provide additional information to the International Joint Commission (IJC), the State of Michigan, and other appropriate planning agencies for evaluating the scientific credibility and the degree of accuracy of the WQA

loading objective for Saginaw Bay. Another objective is to document these predictive results prior to a comprehensive re-survey of Saginaw Bay being conducted in 1980. During the period 1974-1978, phosphorus loads to Saginaw Bay decreased by approximately 50 percent. A unique opportunity exists on Saginaw Bay to assess the effects of phosphorus load reductions, and to test the validity of model predictions. It is anticipated that the re-survey data will be analyzed and made available for comparison with model predictions by mid-1981.

BACKGROUND

The Large Lakes Research Station of the U.S. Environmental Protection Agency has coordinated a sampling and analysis program on Saginaw Bay since 1974. Comprehensive surveys of eutrophication-related parameters were conducted in 1974 and 1975. From 1976 until the present, a monitoring program has been conducted for phosphorus loads and in-lake concentrations. Results of the monitoring program have indicated that the phosphorus load to the bay decreased by approximately 50 percent during the period 1974-1978 (Dolan and Clark 1979). The factors responsible for this reduction were the implementation of advanced wastewater treatment, decreases in tributary flows, and implementation of a detergent phosphorus ban. The Saginaw Bay component of the 1980 Lake Huron Surveillance Plan was expanded in scope to provide a comprehensive data base for assessing the responses of the bay and Southern Lake Huron to this substantial reduction.

The primary water quality criterion used by the TG on Saginaw Bay was taste and odor at the Whitestone Point intake of the Saginaw-Midland Water Supply. Water from this intake constitutes approximately 85 percent of all the water drawn from Saginaw Bay for human use. Secondary criteria used by the TG were filter-clogging and taste and odor problems at the Pinconning and Bay City water filtration plants, and the degree of degradation of the ecosystem in the inner portion of the bay. Annual average total phosphorus concentration was used as the indicator parameter for degree of degradation.

The TG used results of phosphorus load reduction simulations from four different mathematical models on Saginaw Bay. Results from a model developed by Bierman et al. (1975) were used to estimate taste and odor responses, correlated to model output for blue-green biomass. Results from the Bierman model, and from Vollenweider (1976), DiToro et al. (1979), and Chapra (1977, 1978) were used to estimate phosphorus concentration responses. The Bierman, Vollenweider, and DiToro models were calibrated only to the 1974 data. The Chapra model was calibrated to data from 1974-1976; however, this model included only total phosphorus and chlorophyll concentrations. None of the models included spatial segmentation for the bay.

As part of an ongoing project at the Large Lakes Research Station, the Bierman model has been refined, and revised phosphorus load reduction simulations have been conducted. The principal refinements included spatial segmentation of the bay, and calibration to comprehensive sets of field data for both 1974 and 1975. In addition, there has been a more detailed resolution of the input phosphorus loads.

SCOPE

No attempt has been made to develop a comprehensive report on model development or calibration. A brief description of the model is included, along with calibration plots illustrating the comparison of model output with field data for 1974 and 1975. Results are also included from a statistical analysis of goodness-of-fit between model output and field data.

Results of phosphorus load reductions are presented for parameters that relate most directly to the water quality issues in Saginaw Bay. These parameters include taste and odor in the municipal water supply, and annual average total phosphorus concentration. Results are also presented for total phytoplankton biomass and total blue-green phytoplankton biomass. Comparisons are made between the present results and the recommendations of the TG.

MODEL DESCRIPTION

A schematic diagram of the phytoplankton model is shown in Figure 1. The compartments represent the principal variables in the model, and the arrows represent pathways for material transport among the compartments. Figure 2 contains an illustration of the spatial segmentation scheme for Saginaw Bay to which the model was applied. This scheme was based on observed differences in water quality.

The model includes phytoplankton biomass for five functional groups: diatoms, greens, non-N_2-fixing blue-greens, N_2-fixing blue-greens, and "others". The latter category includes primarily dinoflagellates and cryptomonads. Non-N_2-fixing blue-greens consist of those species which have an absolute requirement for dissolved combined nitrogen. N_2-fixing blue-greens consist of those species which have the capability for fixing atmospheric nitrogen, as well as for using dissolved combined nitrogen. The nutrients included in the model are phosphorus, nitrogen, and silicon.

The original version of the model was applied to a single spatial segment which encompassed only the inner portion of Saginaw Bay (Bierman 1976; Bierman et al. 1979). This segment corresponded to segments one, two, and three in the present spatial segmentation scheme. Subsequently, a preliminary calibration was developed with a spatially-segmented version which included the same biological-chemical kinetics as the spatially-simplified version (Bierman and Dolan 1979).

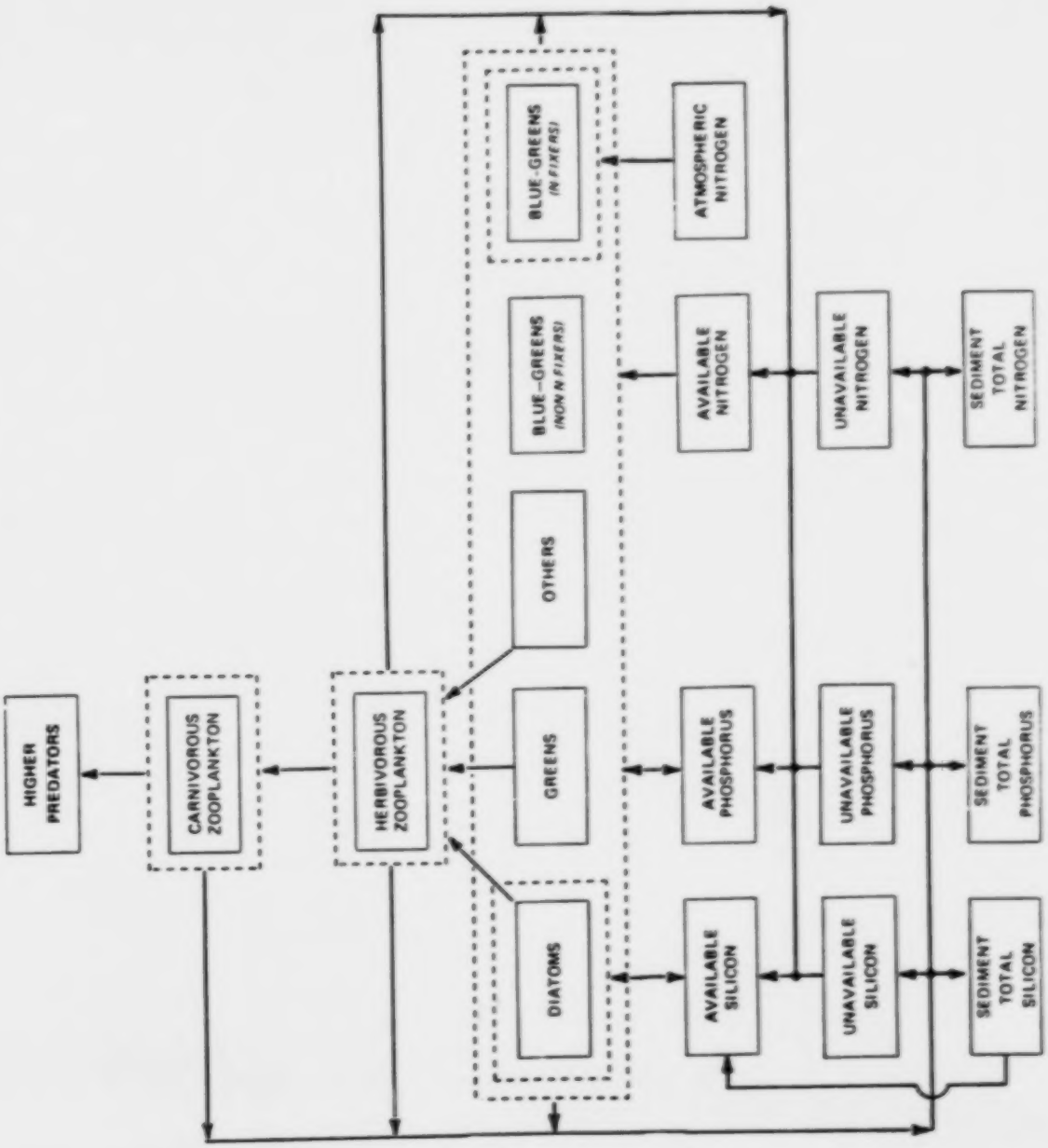

FIGURE 1

Schematic diagram of principal model compartments and interaction pathways

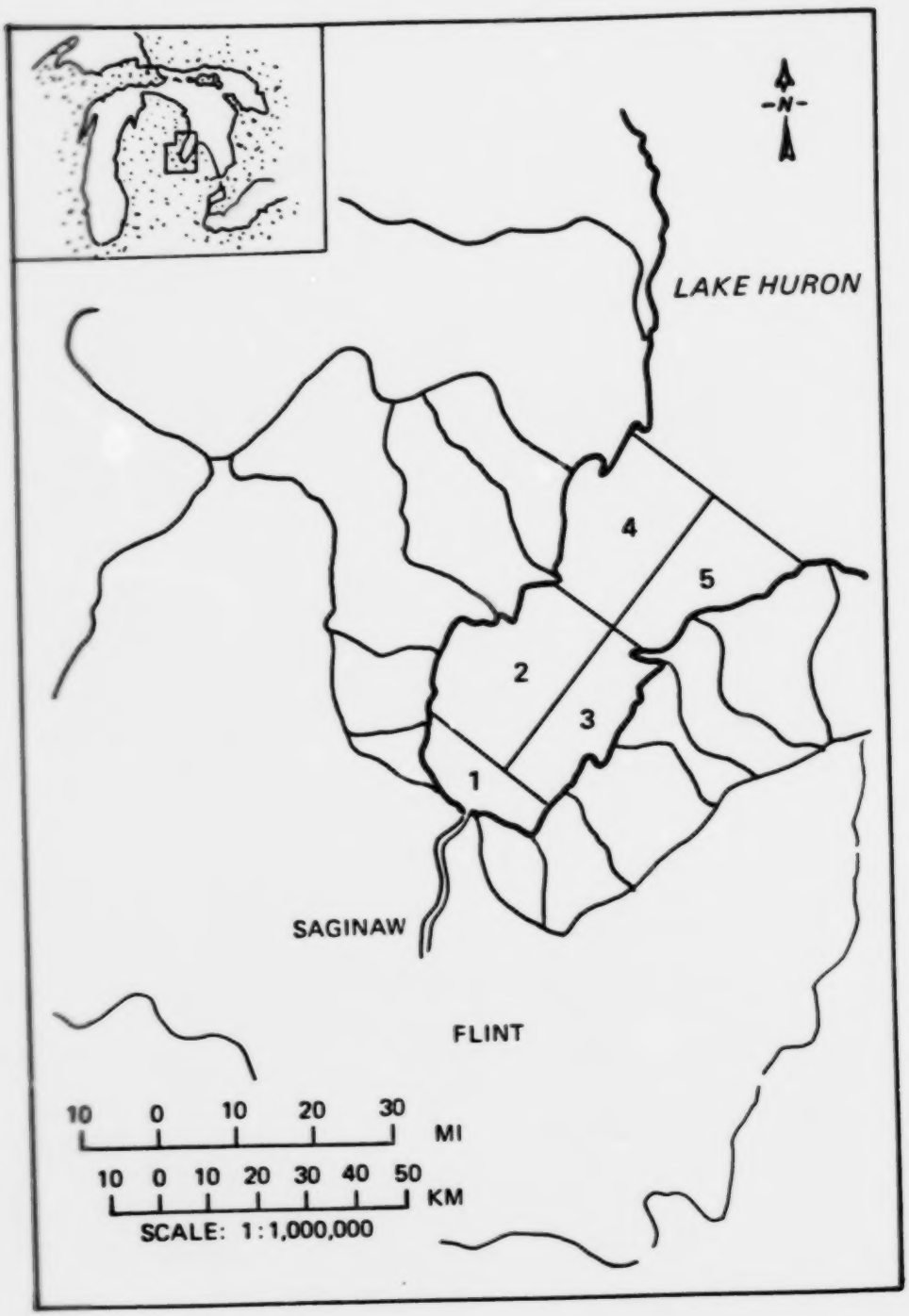

FIGURE 2

Saginaw Bay and spatial segmentation scheme used for the phytoplankton model

The structure of the present version of the model includes the following principal refinements to the original biological-chemical kinetics:

1. Resolution of the zooplankton into separate compartments for herbivorous and carnivorous types.
2. Internal nutrient pool kinetics for silicon in the diatoms.
3. Sediment compartments for total concentrations of phosphorus, nitrogen, and silicon.
4. Wind-driven resuspension of phosphorus, nitrogen and silicon.

In addition, the present application included nutrient loads from tributaries other than the Saginaw River, atmospheric loads, and time variations in incident solar radiation to account for the observed ice cover on the various spatial segments.

MODEL CALIBRATION

The model was calibrated to comprehensive sets of field data for 1974 and 1975. Plots of final calibration results are contained in Appendix A. The ultimate objective of the calibration effort was to identify a unified set of kinetic rate coefficients that would result in the best overall calibration to the data for both years.

The model was applied in an uncoupled mode to the two data sets. Two separate sets of forcing functions were developed, one for each year, and the same model was run independently with each set. There were no differences in kinetic mechanisms or rate coefficients between 1974 and 1975, or among any of the spatial segments. The only differences between the separate applications were caused by differences in nutrient loads, temperatures, water circulation rates, and wind-driven sediment resuspension between the two years.

Model calibration was facilitated by use of the Model Verification Program (MVP) developed by Thomann et al. (1979). The MVP is a system of statistical programs designed to analyze the goodness of fit between model output and field data. In the present application, there were 13 independent model variables in each of five spatial segments for which field data were available. There were 13 sampling cruises in 1974, and 15 sampling cruises in 1975. Consequently, there were 1820 variable-segment-cruise combinations to be evaluated each time the model was run against the two data

sets. It was impossible to rely completely on graphical interpretations of the results. The Student's T-test option of the MVP was used to supplement human intuition in interpreting the results of each run.

Tables I and II contain results of the MVP Student's T-test for the final model calibration to data for 1974 and 1975, respectively. The T-test was applied on a cruise-by-cruise, segment-by-segment basis for each of the 13 independent variables, in each of the two years. Results are reported as percent of sampling cruises for which there was no significant difference between model output and field data at the 95 percent confidence level.

The calibration strategy was to maximize the T-test scores for results in spatial segments two, four, and five. These segments contain approximately 92 percent of the total water volume in Saginaw Bay. Segments one and three are very shallow, containing only 3.5 and 5.0 percent, respectively, of the total water volume in the bay. The average T-test score for results in segments two, four, and five was 86 percent over the two years. In a purely statistical context, this implied that the model output for the 13 variables described the Saginaw Bay system approximately 86 percent as well as the data for these 13 variables described this system.

To relate model output to taste and odor in the Saginaw-Midland Water Supply, a statistical correlation was developed between blue-green biomass concentration and threshold odor measurements. Chartrand (1973) has documented the occurrence of taste and odor problems at the Whitestone Point intake, and the relation of taste and odor to concentrations of blue-green phytoplankton at the intake site. Whitestone Point is located in the outer portion of Saginaw Bay in segment four. Paul (1977) has shown that blue-

TABLE I. STATISTICAL COMPARISON BETWEEN MODEL OUTPUT AND FIELD DATA 1974

Model Variable	Percent of sampling cruises not significantly different Spatial Segment				
	1	2	3	4	5
Diatoms	92	100	100	92	82
Greens	69	92	75	100	90
Others	77	92	58	92	91
Non-N_2 Blue-Greens	62	100	64	100	100
N_2 Blue-Greens	67	89	78	78	89
Herbivorous Zooplankton	60	60	40	89	100
Carnivorous Zooplankton	90	80	60	100	100
Total Phosphorus	100	100	91	91	100
Total Nitrogen	67	73	100	92	91
Dissolved Available Phosphorus	71	62	25	42	42
Dissolved Available Nitrogen	29	77	50	100	75
Dissolved Available Silicon	57	85	15	77	77
Chloride	92	100	85	92	100
Average	72	85	65	88	87

TABLE II. STATISTICAL COMPARISON BETWEEN MODEL OUTPUT AND FIELD DATA 1975

Model Variable	Percent of sampling cruises not significantly different Spatial Segment				
	1	2	3	4	5
Diatoms	53	73	50	92	75
Greens	80	87	91	100	92
Others	80	93	100	100	100
Non-N_2 Blue-Greens	43	86	91	92	100
N_2 Blue-Greens	64	82	67	80	100
Herbivorous Zooplankton	58	69	44	77	75
Carnivorous Zooplankton	92	62	89	85	100
Total Phosphorus	80	100	82	100	100
Total Nitrogen	60	100	100	100	93
Dissolved Available Phosphorus	54	64	56	57	46
Dissolved Available Nitrogen	57	75	40	67	71
Dissolved Available Silicon	20	53	25	80	71
Chloride	87	100	100	100	100
Average	64	80	72	87	86

green phytoplankton produced in the inner bay and transported by water movements to the outer bay are responsible for taste and odor at this intake. Measured blue-green phytoplankton concentrations in segment two were correlated with threshold odor measurements at the intake site. The following correlation was found to be statistically significant at the 99 percent confidence level ($r^2 = 0.76$):

$$T.O. = 1.78 + 2.4\ (BG)$$

where: T.O. = threshold odor number

BG = total blue-green biomass concentration in segment two, mg dry weight/liter.

Statistically, at the 95 percent confidence level, it was found that total blue-green biomass concentrations greater than 1.14 mg dry weight/liter in segment two corresponded to violations of the U.S. Public Health Service standard for threshold odor (T.O. = 3) at the Whitestone Point intake.

Output from the calibrated model compared favorably with the corresponding threshold odor measurements. Model results for total blue-green biomass in segment two correspond to a period of 57 days in 1974 when threshold odor would be in violation at the Whitestone Point intake. Measurements at the intake site showed violations on 72 days. The relative error between observed and calculated values was 21 percent.

Table III contains numerical values for selected calibration results for 1974 and 1975 conditions. Phytoplankton biomass concentrations and annual average total phsophorus concentrations were higher in 1975 than in 1974. Differences in principal forcing functions between the two years are summarized in Table IV. It is significant to note that total phosphorus

TABLE III. SUMMARY OF MODEL OUTPUT FOR FINAL CALIBRATION

Parameter		1974	1975
Annual Average Total Phosphorus Concentration, µg/l			
	Segment 2	18.3	21.6
	Segment 4	5.72	7.51
Peak Total Biomass Concentration, mg/l			
	Segment 2	6.27	9.49
	Segment 4	2.13	3.66
Peak Total Blue-Green Biomass Concentration, mg/l			
	Segment 2	2.40	3.46
	Segment 4	0.289	1.15
Gross Total Biomass Production, mg/l			
	Segment 2	64.8	83.0
	Segment 4	24.2	40.2
Gross Total Blue-Green Biomass Production, mg/l			
	Segment 2	15.0	17.3
	Segment 4	2.18	4.41
Number of Days Where Taste and Odor >3 with Probability >0.95		57	46

TABLE IV. DIFFERENCES IN PRINCIPAL FORCING FUNCTIONS BETWEEN 1974 AND 1975 ON SAGINAW BAY

Parameter	1974	1975
Saginaw River Phosphorus Loads, metric tonnes		
Total Phosphorus	1266	1470
Available Phosphorus	282	410
Time Distribution of Saginaw River Phosphorus Loads		
Phosphorus Loads During First Half of Year, metric tonnes		
Total Phosphorus	1000 (79%)	779 (53%)
Available Phosphorus	172 (61%)	214 (52%)
Phosphorus Loads During Second Half of Year, metric tonnes		
Total Phosphorus	266 (21%)	691 (47%)
Available Phosphorus	110 (39%)	196 (48%)
Cruise Average Temperature, °C		
Segment 2	12.0	13.9
Segment 4	9.82	11.1
Number of Days Where Wind Speed Exceeded Threshold for Resuspension	29	40

load, temperature, and wind-driven sediment resuspension were all greater in 1975 than in 1974. Of particular significance was the fact that available phosphorus loadings were higher in 1975 than 1974 in both the first and the second half of the year.

PHSOPHORUS LOAD REDUCTION SIMULATIONS

Methodology

Phosphorus load reduction simulations were conducted by running the calibrated model with reduced phosphorus loads for the Saginaw River. Loads for all other constituents in the Saginaw River were held constant at the calibration levels. Loads for all constituents from other tributaries and from atmospheric sources, including phosphorus, were also held constant at the calibration levels. The calibration phosphorus loads for 1974 and 1975 are contained in Tables V and VI, respectively. In each year, approximately 90 percent of the total phosphorus load to Saginaw Bay was from the Saginaw River.

All results have been expressed in terms of annual average total phosphorus concentration, total phytoplankton biomass, total blue-green phytoplankton biomass, and taste and odor in the municipal water supply. These parameters relate most directly to the principal water quality issues in Saginaw Bay. Taste and odor is probably the single most pertinent and direct response parameter in terms of water quality.

Results have been presented only for responses in segments two and four. The most seriously degraded area of Saginaw Bay is the inner portion, of which segment two contains 73 percent of the total water volume. Also, it was shown that blue-green phytoplankton in segment two were strongly correlated with taste and odor in the largest municipal water supply on the bay.

TABLE V. 1974 PHOSPHORUS LOADINGS TO SAGINAW BAY
IN METRIC TONNES PER YEAR

Spatial Segment	Source		Total
	Tributary	Atmosphere	
Total Phosphorus			
1	1266	6	1272
2	50	22	72
3	10	9	19
4	15	16	31
5	28	17	45
Whole Bay	1369 (95%)	70 (5%)	1439
Dissolved Ortho-Phosphorus			
1	282	2	284
2	12	6	18
3	2	3	5
4	4	5	9
5	6	5	11
Whole Bay	306 (94%)	21 (6%)	327

TABLE VI. 1975 PHOSPHORUS LOADINGS TO SAGINAW BAY
IN METRIC TONNES PER YEAR

Spatial Segment	Source		Total
	Tributary	Atmosphere	
Total Phosphorus			
1	1470	6	1476
2	50	22	72
3	10	9	19
4	15	16	31
5	28	17	45
Whole Bay	1573 (96%)	70 (4%)	1643
Dissolved Ortho-Phosphorus			
1	410	2	412
2	16	6	22
3	4	3	7
4	5	5	10
5	10	5	15
Whole Bay	445 (95%)	21 (5%)	466

Segment four is of interest because it contains the highest quality water in the bay. This segment receives most of the direct inflow from the main body of Lake Huron. The responses of segment four provide the sharpest contrast with the responses of segment two.

Phosphorus Availability

As an operational assumption, dissolved ortho-phosphorus was considered to be algal-available phosphorus. Total phosphorus minus dissolved ortho-phosphorus was considered to be algal-unavailable phosphorus. For the calibration data sets, measurements were conducted for both types of phosphorus loads at the delivery point to the system. A problem arose under load reduction conditions because the ratio of available to total phosphorus had to be estimated for the major source types.

The two major sources of tributary phosphorus loads were point sources and diffuse sources. It is generally accepted that point sources have a higher ratio of available to total phosphorus than diffuse sources. The problem in developing load reduction scenarios was that this ratio had to be estimated at the delivery point. The net ratio of available to total phosphorus at this point is usually not the weighted average of the ratios for the individual sources. This is because physical, chemical, and biological processes in tributaries can substantially change this ratio before final delivery to the system. For example, total phosphorus loads from point sources in the Saginaw River were 630 metric tonnes (mt) in 1974 and 619 mt in 1975 (M. Stifler, Michigan Department of Natural Resources, personal communication, March 26, 1979). DePinto et al. (1979) reported that the average ratio of available to total phosphorus in 23 effluent samples from four different treatment plants in the Lower Lakes was 72 percent. Since

phosphorus loads from point sources constituted almost half of the total phosphorus load, the ratio of available to total phosphorus at the Saginaw River mouth should have been at least 36 percent. From the data in Tables V and VI, the measured values were 22 and 28 percent, respectively, for 1974 and 1975.

Table VII contains the complete resolution of Saginaw River phosphorus loads by source type and availability that was used for all of the load reduction simulations. It was assumed that the effective ratio of available to total phosphorus for point sources was 34 percent at the Saginaw River mouth. This ratio was developed on the basis of two assumptions: one, that the ratio of available to total phosphorus for point loads was the same for 1974 and 1975; and two, that the ratio for point sources was higher than that for diffuse sources. An upper limit for the ratio of available to total phosphorus for point sources was defined by assuming that all measured available phosphorus in each year was from point sources:

$$\frac{\text{Measured available phosphorus}}{\text{Total point source phosphorus}} = \frac{282 \text{ mt}}{630 \text{ mt}} = 0.448 \quad (1974)$$

$$= \frac{410 \text{ mt}}{619 \text{ mt}} = 0.662 \quad (1975)$$

A lower limit for this ratio was defined by assuming that its value was equal to the ratio of available to total phosphorus in the total measured load:

$$\frac{\text{Measured available phosphorus}}{\text{Measured total phosphorus}} = \frac{282 \text{ mt}}{1266 \text{ mt}} = 0.223 \quad (1974)$$

$$= \frac{410 \text{ mt}}{1470 \text{ mt}} = 0.279 \quad (1975)$$

TABLE VII. SAGINAW RIVER PHOSPHORUS LOADS BY SOURCE TYPE AND AVAILABILITY IN METRIC TONNES PER YEAR

Load	1974	1975
Point Loads		
Available	212 (34%)	208 (34%)
Unavailable	418 (66%)	411 (66%)
Total Point	630	619
Diffuse Loads		
Available	70 (11%)	202 (24%)
Unavailable	566 (89%)	649 (76%)
Total Diffuse	636	851
Total Loads		
Available	282 (22%)	410 (28%)
Unavailable	984 (78%)	1060 (72%)
Total	1266	1470

Point load corresponding to effluent concentration of 1 mg/l for all municipal plants greater than 1 MGD is 153.

The value of 66.2 percent was eliminated as an upper limit because it would have led to a higher value for available point load in 1974 than was actually measured for the total phosphorus load. The final ratio used was the average of 44.8 and 22.3 percent. Finally, the assumption was made that the ratio of available to total phosphorus for point sources did not change as a result of assumed treatment levels in the load reduction simulations. This assumption was consistent with the results of DePinto et al. (1979).

Each load reduction scenario was developed by assuming a particular combination of point and/or diffuse source reductions. It should be noted that the treatment strategies used to develop each of the reduced loads were not unique. Further, when the same strategy was applied to the 1974 and 1975 phosphorus loads, the resultant load for 1975 was always higher because the diffuse source component of the 1975 load was higher than that of the 1974 load.

Uncertainties

A degree of uncertainty always exists in predictive results based on phosphorus load reduction simulations. Uncertainties can arise from three basic sources:

1. Model errors.
2. Data uncertainties.
3. Uncertainties in forcing functions under conditions of reduced phosphorus loads.

Model errors can be either errors in the calibration, or errors caused by failure of the mechanisms in the model to account for system responses under loading changes. Data uncertainties are primarily related to uncertainties in the determination of calibration phosphorus loads. It is difficult to

estimate the degree of prediction uncertainty due to model and data uncertainties.

Uncertainties in forcing functions probably account for most of the prediction uncertainty in the case of Saginaw Bay. In using predictive results, the underlying assumption is that the system responses under conditions of reduced phosphorus loads can be attributed completely to the changes in loads. Uncertainties are introduced to the extent that system responses are influenced by factors other than changes in phosphorus loads. Saginaw Bay is highly dynamic and has a short hydraulic detention time (45-120 days). The response of the bay in any single year is greatly influenced by the particular conditions for rainfall, surface runoff, water circulation rates, wind-driven resuspension, and temperature. Consequently, the validity of predictive results for Saginaw Bay depends on the accuracy of estimates for forcing functions under future conditions of reduced phosphorus loads.

The approach used to minimize uncertainties in forcing functions was to run all phosphorus load reduction simulations relative to both 1974 and 1975 conditions. It was shown earlier that the principal forcing functions were substantially different for these two years. To the extent that the forcing funtions under reduced loading conditions will be bounded by these conditions, the prediction uncertainty of the present results has been minimized. It was decided that this approach was more realistic than attempting to contrive a composite set of forcing functions for an "average year". In any case, a definitive test of the model will be conducted by running the calibrated model with the actual loads and forcing functions for 1980, and comparing model results with actual system responses.

Results

Results of phosphorus load reduction simulations have been tabulated relative to 1974 and 1975 conditions for seven selected phosphorus loads (Tables VIII and IX). These results can be referenced to the final calibration results for 1974 and 1975 in Table III. Results are presented for principal response parameters in graphical form for actual values and percentage reductions. With the exception of taste and odor, graphical results are presented only relative to 1974 conditions.

Annual average total phosphorus concentration in Saginaw Bay showed a greater response in segment two than in segment four (Figures 3 and 8). The concentration in segment four tended to approach the value of the boundary concentration with Lake Huron as phosphorus load decreased. The concentration in segment two did not approach zero in the limit of minimum phosphorus load. This behavior was partly the result of a "background" phosphorus load to Saginaw Bay from non-Saginaw River sources of 173 metric tonnes per year (mta).

Peak total biomass concentrations did not substantially decrease in either segments two or four in response to phosphorus load reductions (Figures 4 and 9). Peak total biomass concentration consisted primarily of the spring diatom peak. The results were consistent with the hypothesis that phosphorus concentrations were sufficiently high in the spring such that the diatom crops were not severely nutrient deficient. On a percentage basis, the peak crop in segment four showed a greater response than the peak crop in segment two.

The most significant feature of the results was the dramatic reduction in peak total blue-green biomass concentrations in response to phosphorus

TABLE VIII. SUMMARY OF RESPONSES TO PHOSPHORUS LOAD REDUCTIONS RELATIVE TO 1974 CONDITIONS

Parameter	Saginaw River Total Phosphorus Load (mta) 789[1]	713[2]	662[3]	598[4]	535[5]	440[6]	210[7]
Annual Average Total Phosphorus Concentration, µg/l							
Segment 2	16.5	16.0	16.0	15.8	15.5	15.2	14.4
Segment 4	5.32	5.26	5.22	5.17	5.13	5.05	4.88
Peak Total Biomass Concentration, mg/l							
Segment 2	5.66	5.48	5.58	5.56	5.52	5.28	5.04
Segment 4	1.85	1.79	1.81	1.79	1.76	1.66	1.51
Peak Total Blue-Green Biomass Concentration, mg/l							
Segment 2	1.66	1.53	1.45	1.40	1.31	1.17	0.899
Segment 4	0.244	0.226	0.223	0.211	0.198	0.173	0.124
Gross Total Biomass Production, mg/l							
Segment 2	56.6	55.2	54.9	54.1	53.3	52.0	49.6
Segment 4	21.3	20.9	20.9	20.7	20.4	20.1	19.6
Gross Total Blue-Green Biomass Production, mg/l							
Segment 2	11.3	10.4	10.0	9.35	8.68	7.70	5.87
Segment 4	1.97	1.86	1.84	1.76	1.68	1.54	1.25
Number of Days Where Taste and Odor >3 With Probability >0.95	39	34	31	25	15	5	0

[1]Point sources at 1 mg/l - no non-point source reductions.
[2]Point sources at 0.5 mg/l - no non-point source reductions.
[3]Point sources at 1 mg/l + 20% reduction in non-point sources.
[4]Point sources at 1 mg/l + 30% reduction in non-point sources.
[5]Point sources at 1 mg/l + 40% reduction in non-point sources.
[6]1978 Water Quality Agreement Load - point sources at 0.5 mg/l + 43% reduction in non-point sources.
[7]IJC, 1980 - point sources at 0.5 mg/l + 79% reduction in non-point sources.

TABLE IX. SUMMARY OF RESPONSES TO PHOSPHORUS LOAD REDUCTIONS RELATIVE TO 1975 CONDITIONS

Parameter	Saginaw River Total Phosphorus Load (mta) 1003[1]	926[2]	832[3]	747[4]	662[5]	440[6]	210[7]
Annual Average Total Phosphorus Concentration, µg/l							
Segment 2	18.0	17.4	16.8	16.3	15.7	14.3	12.9
Segment 4	6.74	6.64	6.51	6.39	6.27	5.96	5.66
Peak Total Biomass Concentration, mg/l							
Segment 2	8.04	7.61	7.37	7.00	6.73	5.87	4.83
Segment 4	2.93	2.86	2.80	2.73	2.66	2.47	2.29
Peak Total Blue-Green Biomass Concentration, mg/l							
Segment 2	2.39	2.18	1.94	1.71	1.46	0.851	0.336
Segment 4	0.891	0.838	0.779	0.718	0.661	0.532	0.435
Gross Total Biomass Production, mg/l							
Segment 2	68.6	65.6	61.5	57.6	53.8	46.7	42.3
Segment 4	34.6	34.0	33.3	32.7	32.3	31.4	30.9
Gross Total Blue-Green Biomass Production, mg/l							
Segment 2	12.7	11.8	10.7	9.50	8.26	4.72	2.36
Segment 4	3.36	3.16	2.96	2.76	2.53	1.86	1.46
Number of Days Where Taste and Odor >3 With Probability >0.95	31	28	25	21	15	0	0

[1]Point sources at 1 mg/l - no non-point source reductions.
[2]Point sources at 0.5 mg/l - no non-point source reductions.
[3]Point sources at 1 mg/l + 20% reduction in non-point sources.
[4]Point sources at 1 mg/l + 30% reduction in non-point sources.
[5]Point sources at 1 mg/l + 40% reduction in non-point sources.
[6]1978 Water Quality Agreement Load - point sources at 0.5 mg/l + 57% reduction in non-point sources.
[7]IJC, 1980 - point sources at 0.5 mg/l + 84% reduction in non-point sources.

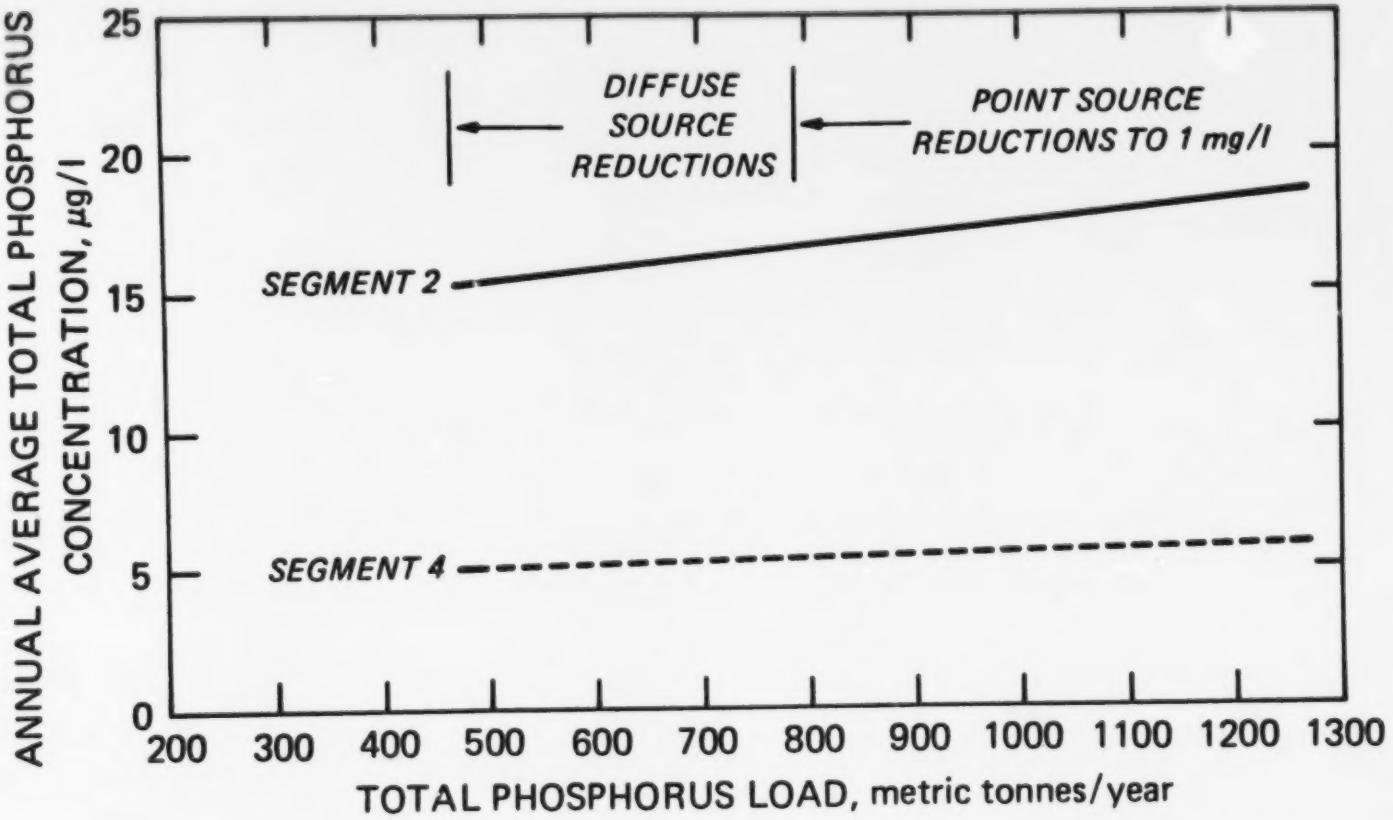

FIGURE 3

Relationship between annual average total phosphorus concentration and Saginaw River total phosphorus load, relative to 1974 conditions

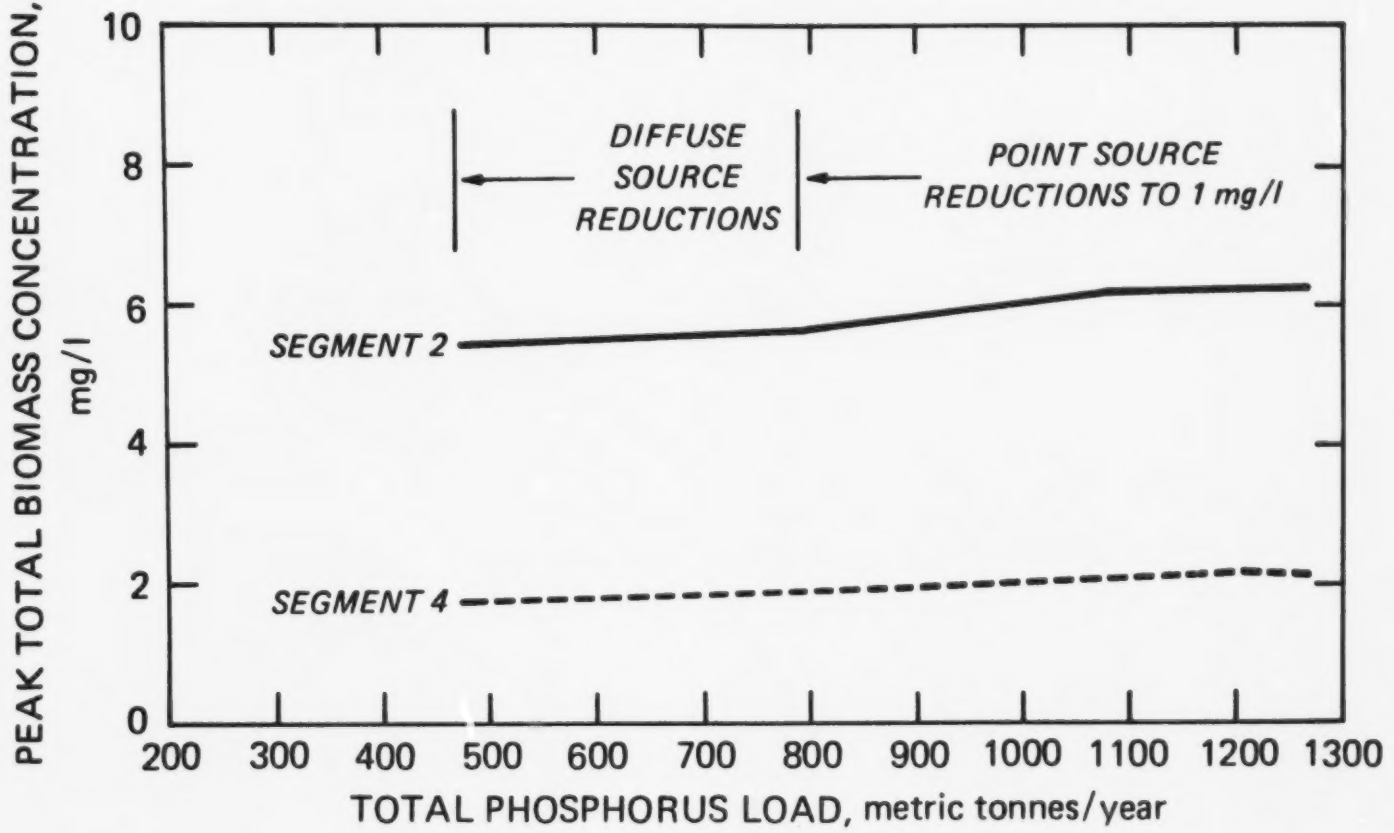

FIGURE 4

Relationship between peak total biomass concentrations and Saginaw River total phosphorus load, relative to 1974 conditions

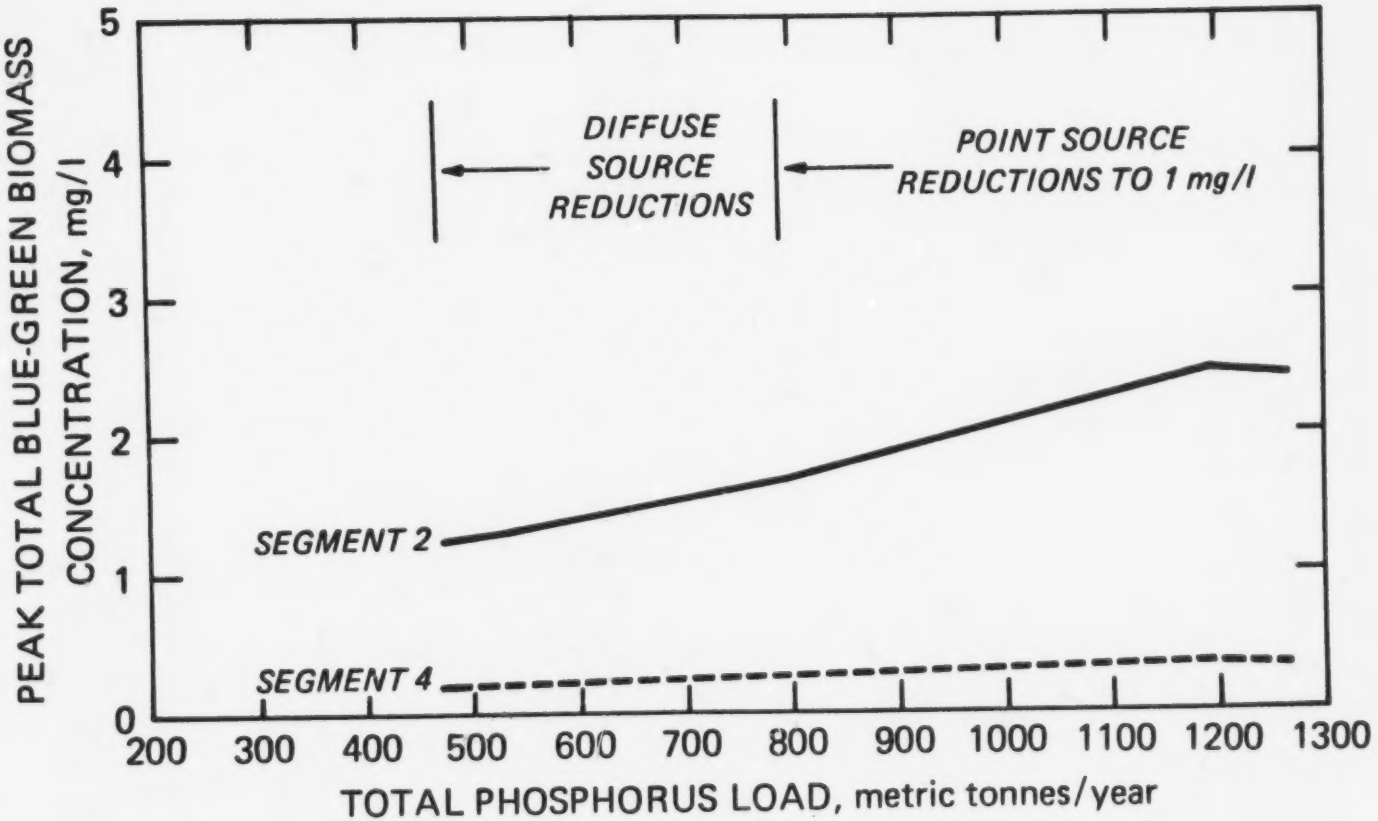

FIGURE 5

Relationship between peak total blue-green biomass concentration and Saginaw River total phosphorus load, relative to 1974 conditions

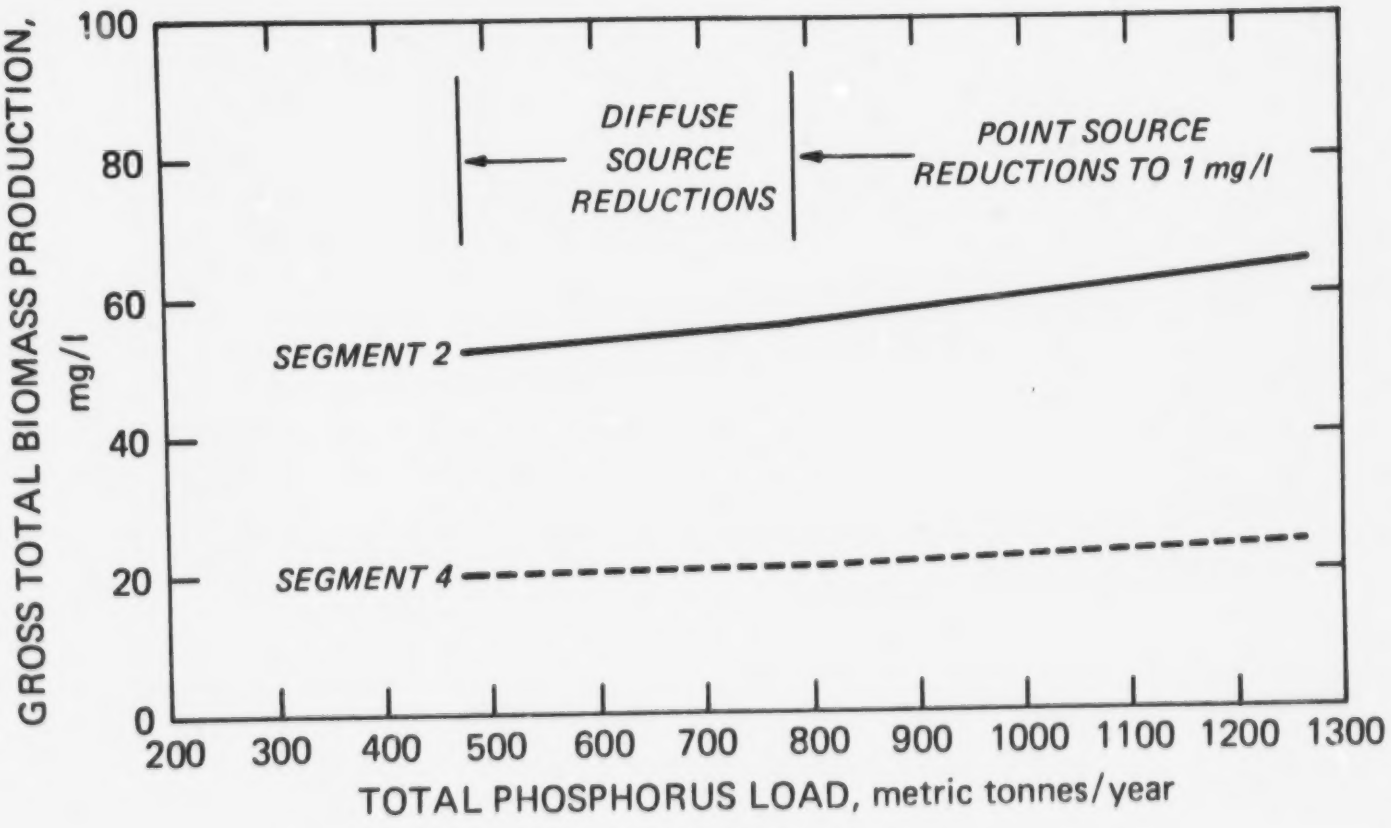

FIGURE 6

Relationship between gross total biomass production and Saginaw River total phosphorus load, relative to 1974 conditions

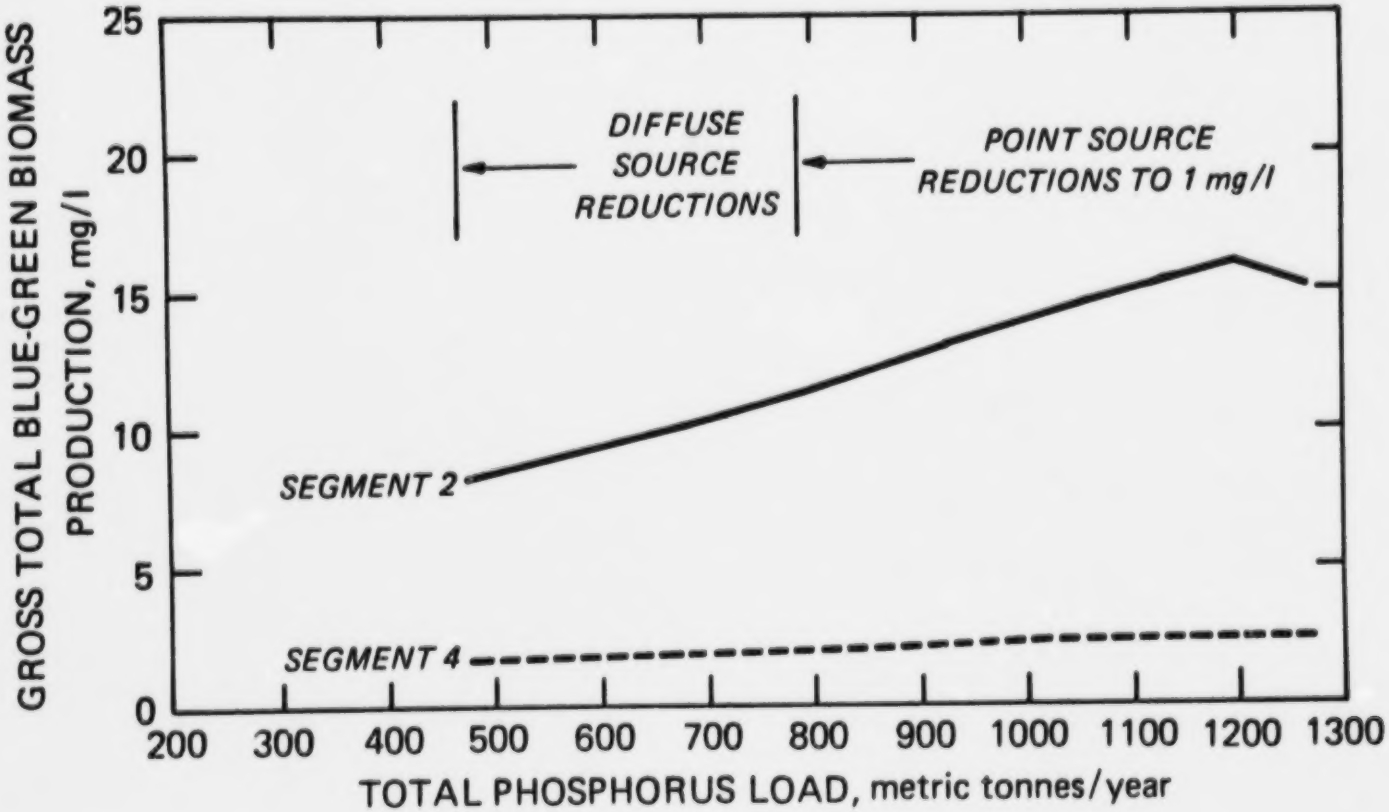

FIGURE 7

Relationship between gross total blue-green biomass production and Saginaw River total phosphorus load, relative to 1974 conditions

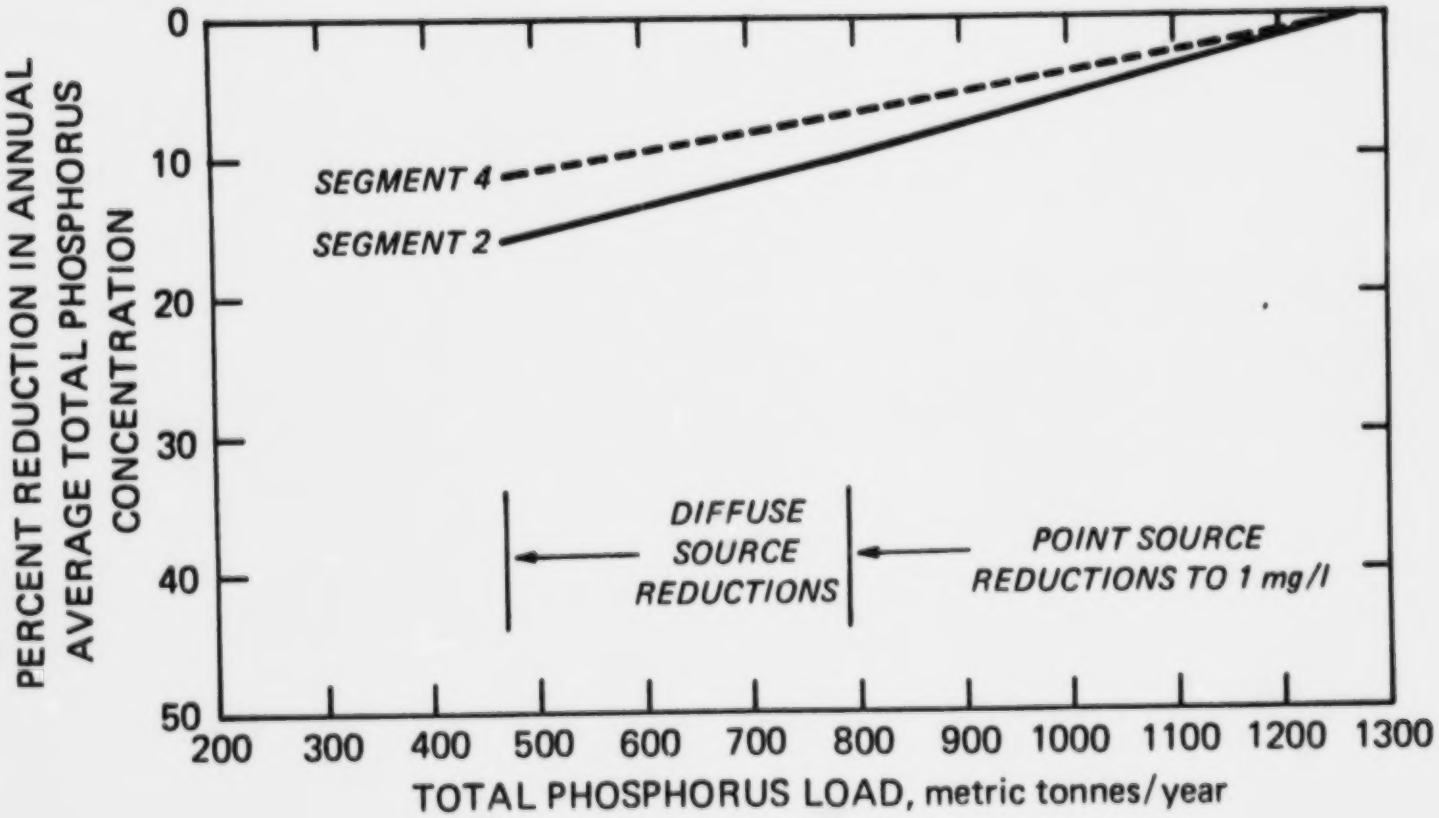

FIGURE 8

Relationship between percent reduction in annual average total phosphorus concentration and Saginaw River total phosphorus load, relative to 1974 conditions

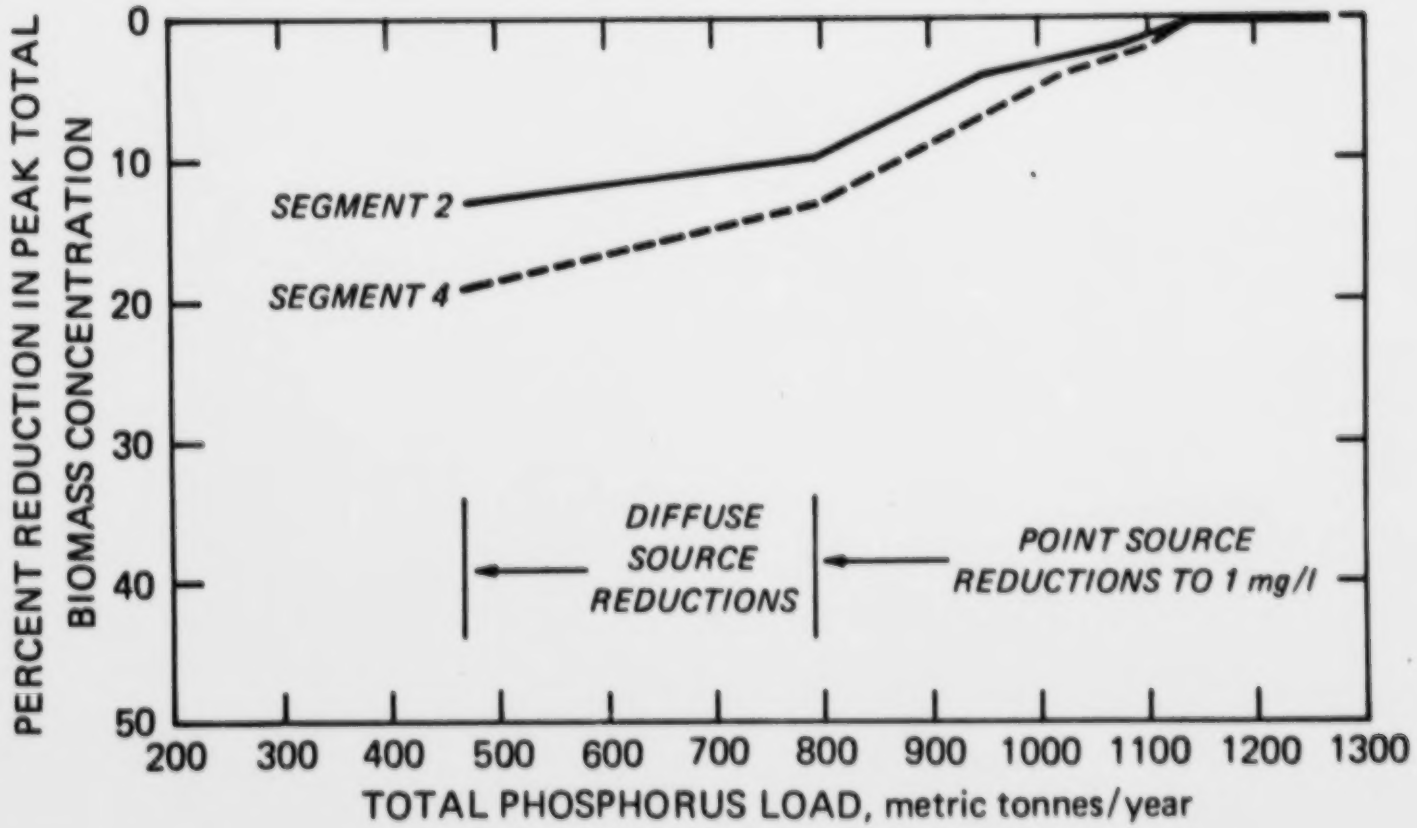

FIGURE 9

Relationship between percent reduction in peak total biomass concentration and Saginaw River total phosphorus load, relative to 1974 conditions

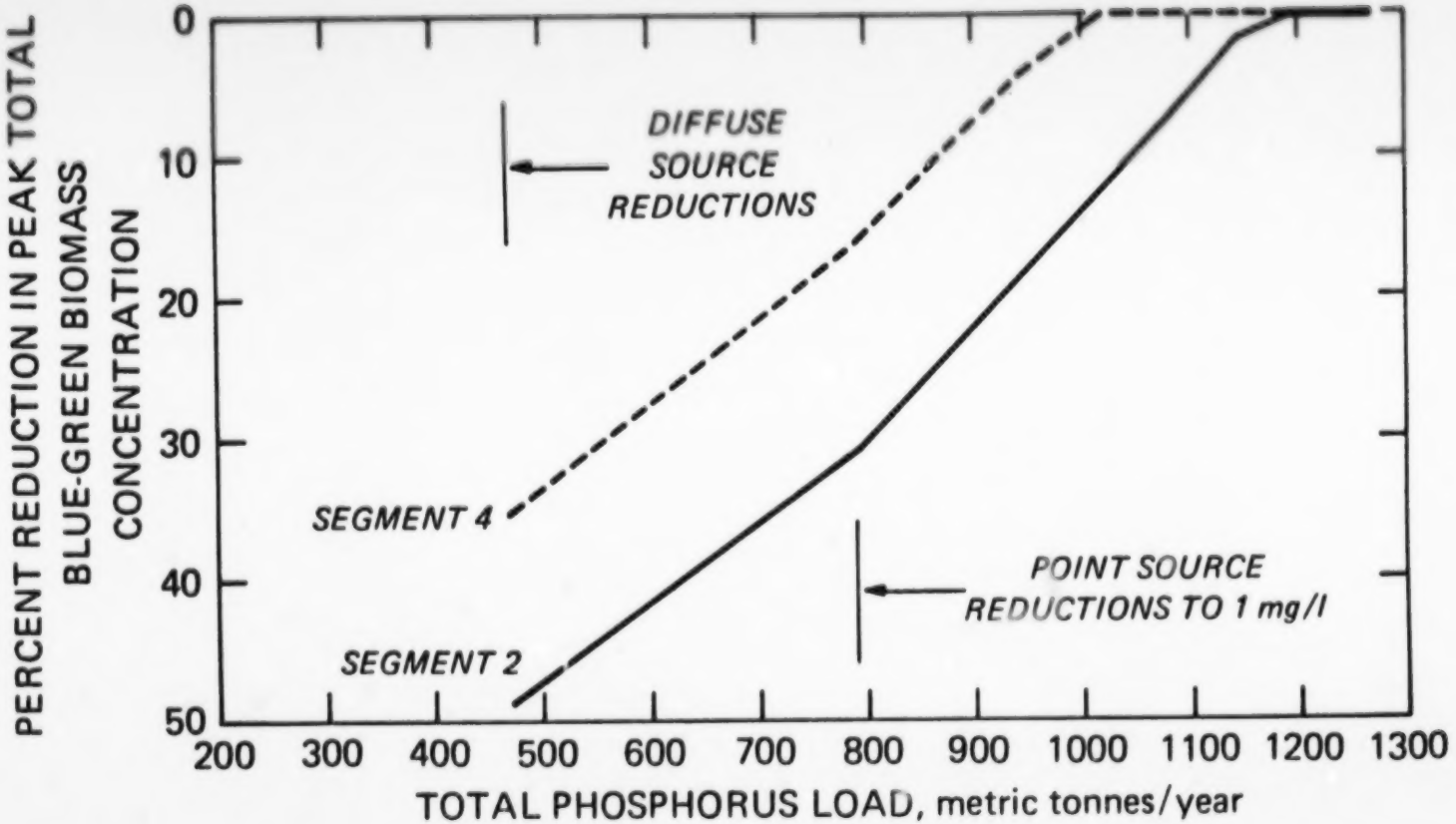

FIGURE 10

Relationship between percent reduction in peak total blue-green biomass concentration and Saginaw River total phosphorus load, relative to 1974 conditions

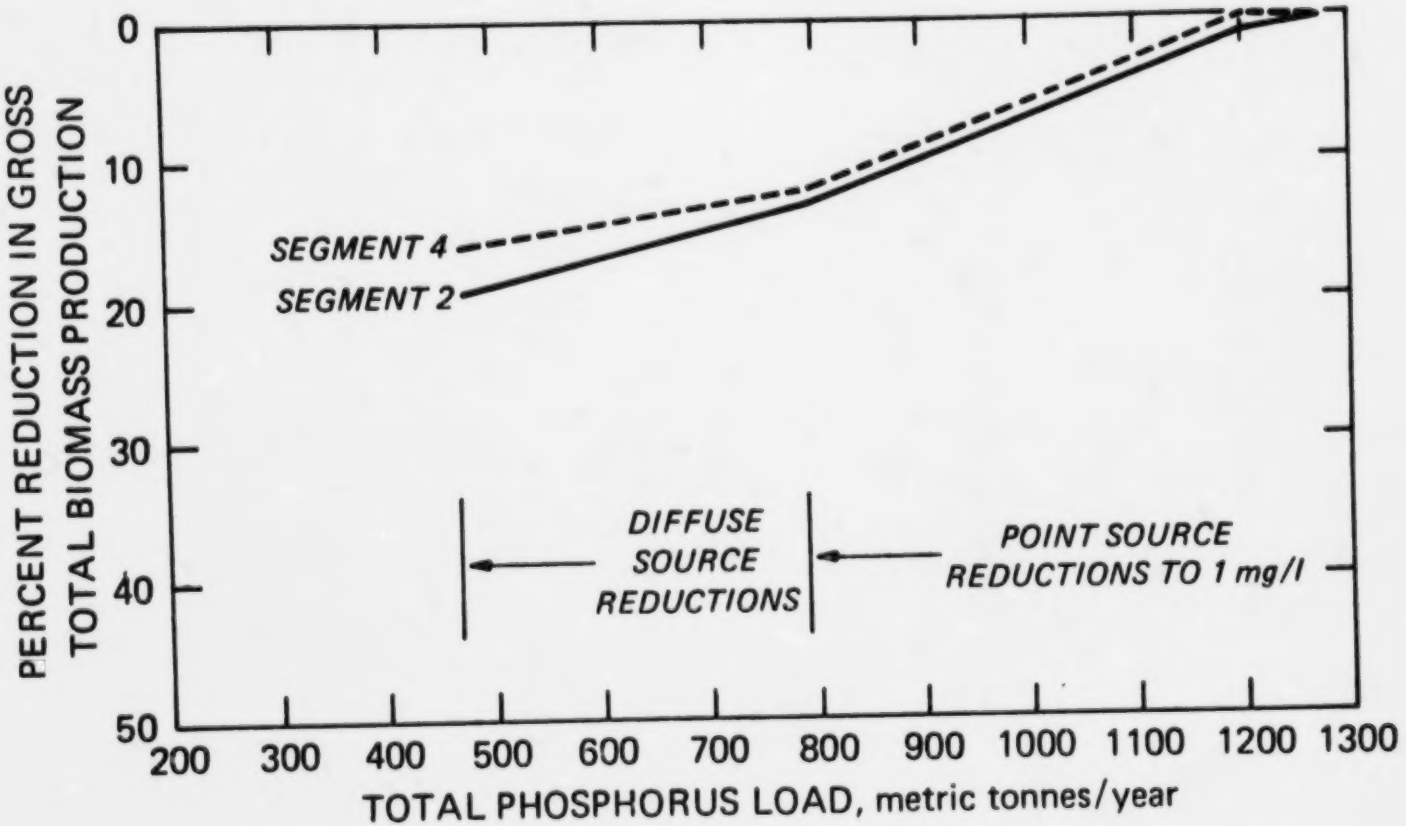

FIGURE 11

Relationship between percent reduction in gross total biomass production and Saginaw River total phosphorus load, relative to 1974 conditions

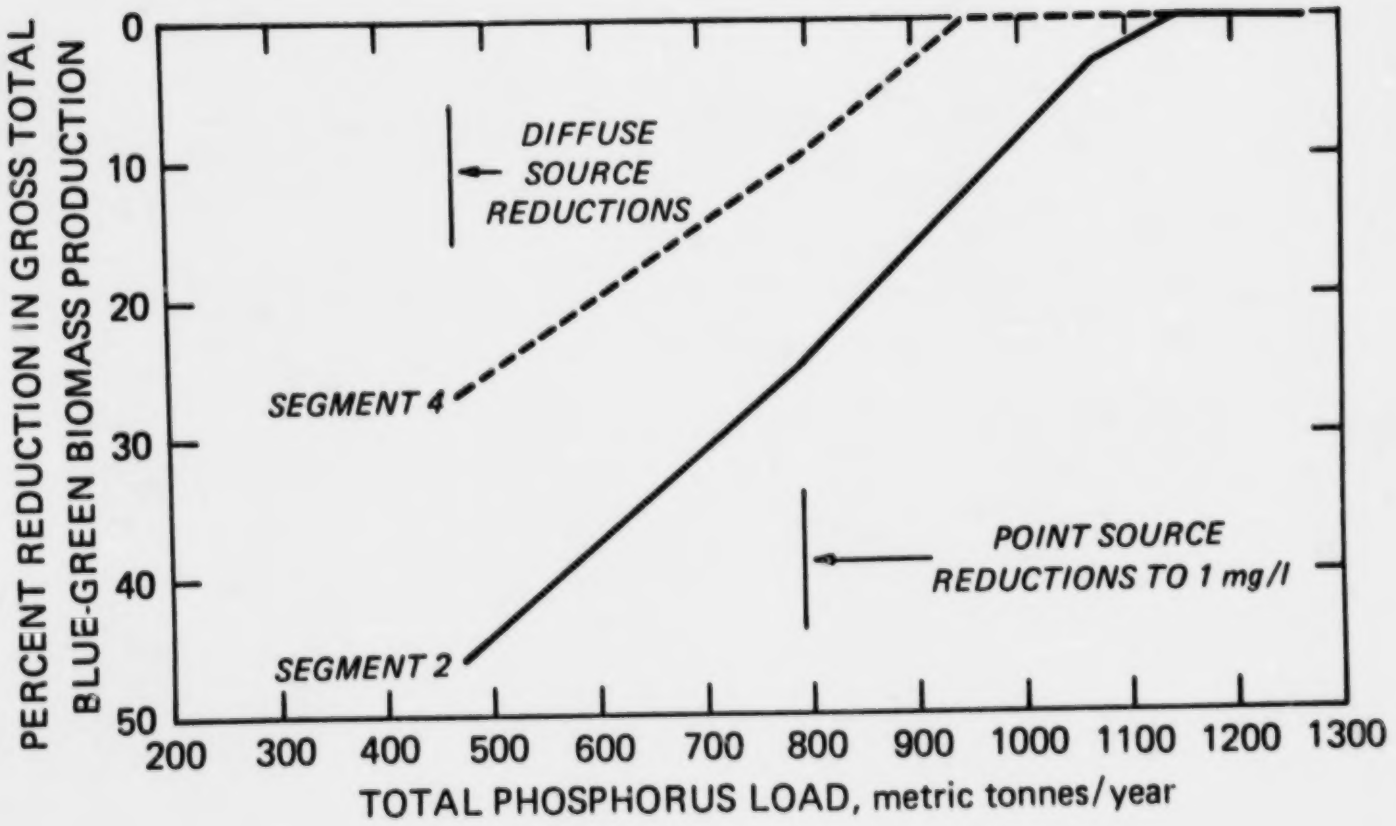

FIGURE 12

Relationship between percent reduction in gross total blue-green biomass production and Saginaw River total phosphorus load, relative to 1974 conditions

load reductions (Figures 5 and 10). From a water quality standpoint, it was significant that the response of the blue-greens in segment two was much greater than the response in segment four. The blue-greens in segment two responded almost in direct proportion to the magnitude of the phosphorus load reduction, whereas the blue-greens in segment four responded in a much lower proportion.

Results for gross biomass production showed the same general trends as results for peak biomass concentration. Gross biomass production reflects the total quantity of phytoplankton biomass produced over the annual cycle, in contrast to a peak concentration value at a single point in time. Responses based on gross biomass production are probably more indicative of water quality responses than are results based on peak concentrations.

Results for gross total biomass production are shown in Figures 6 and 11, and results for gross total blue-green biomass production are shown in Figures 7 and 12. In segment four, responses were not as great on the basis of gross biomass production as on the basis of peak concentration. In segment two, there was a greater response for total biomass production, and a somewhat lesser response for total blue-green biomass production, compared to responses on the basis of peak concentrations. Responses for total gross production were inverted, compared with results for peak total concentration. On a percentage basis, total biomass production in segment two showed a greater response than total biomass production in segment four.

Perhaps the single most meaningful response parameter for Saginaw Bay is taste and odor in the municipal water supply. This parameter is related to perception of water quality by the public, and to increased treatment costs at the water utilities. Figure 13 illustrates results of phosphorus load

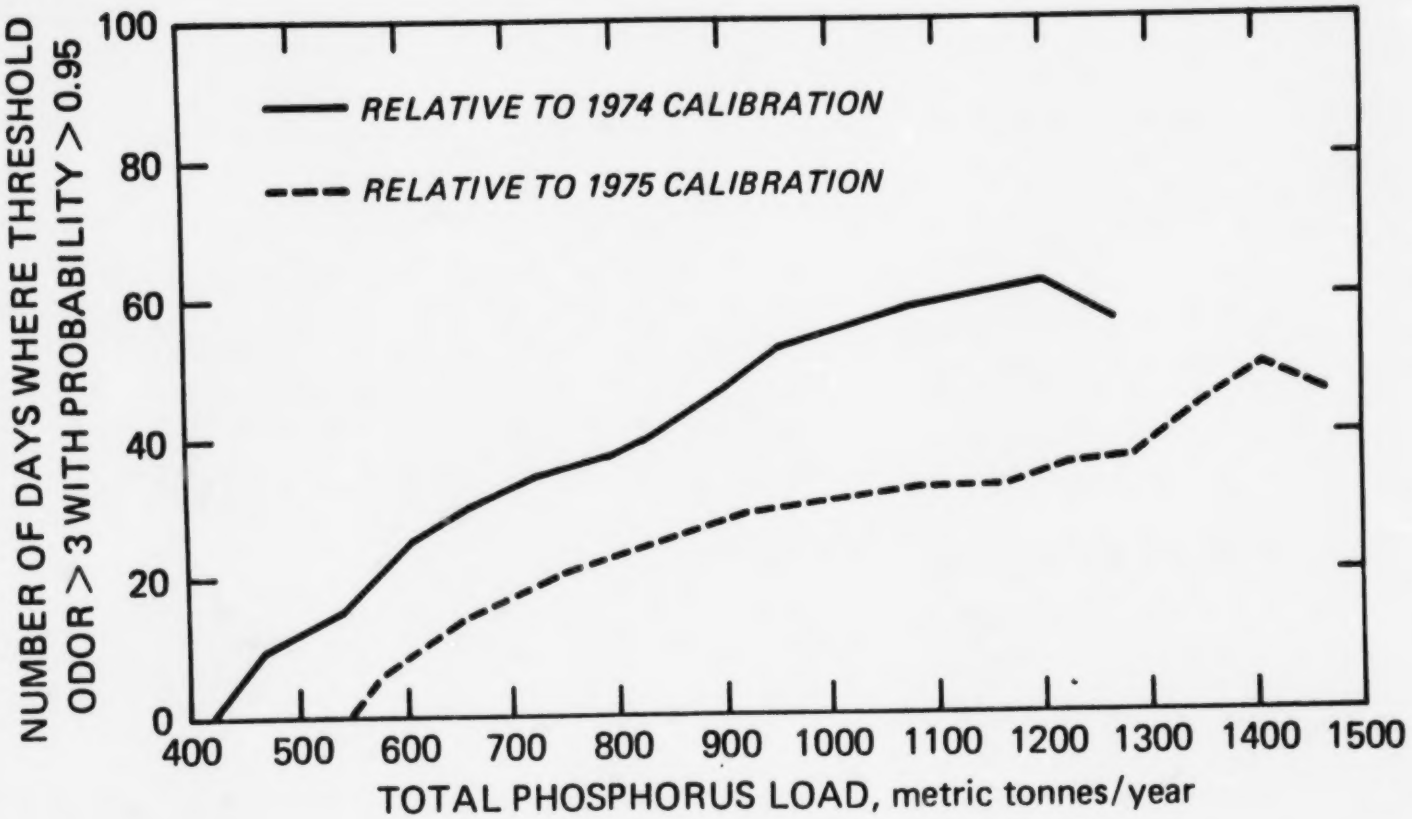

FIGURE 13

Relationship between taste and odor in the raw water supply at the Whitestone Point intake and Saginaw River total phosphorus load

reduction simulations in terms of number of days where violations of the U.S. Public Health Service standard for threshold odor would be expected to occur. The results indicated a relatively flat response as the phosphorus loads were reduced from calibration levels to approximately 900-1000 mta. At this loading level, results corresponded to a period for violations of one to two months, depending on the particular conditions. As the phosphorus loads were reduced below 900 mta, threshold odor showed a much greater response. At an average phosphorus load of 485 mta for 1974 and 1975 conditions, results indicated that at the 95 percent confidence level, no violations of the threshold odor standard would occur.

Comparison with Results of Task Group III

It is appropriate to compare the present results with the results of Task Group III. The approach used was to compare phosphorus loads from the two studies in terms of requirements for meeting the same water quality objectives. This comparison was not exact because of differences in model spatial segmentation, and compilation of total phosphorus loads. None of the models used by the TG for Saginaw Bay were spatially segmented. All four models contained a single spatial segment for the bay which encompassed a water volume approximately equivalent to the sum of segments one, two, and three in the present study. In addition, the total phosphorus loads to Saginaw Bay used by the TG included only the Saginaw River and atmospheric sources to the inner bay. The present study included loads from non-Saginaw River tributaries and atmospheric sources for the entire bay. The effect of these loading differences on the results was not straightforward. Non-Saginaw River tributary loads and atmospheric loads do not contribute to phosphorus dynamics in the inner bay in simple proportion to

their magnitudes because these sources are spatially distributed about the entire bay.

Mindful of the preceding qualifications, a comparison of results from the present study with those of Task Group III is presented in Table X. Results for threshold odor can be compared more directly than results for annual average total phosphorus concentration because the threshold odor objective was the same for both studies. The phosphorus load required to meet the threshold odor standard from the present results agreed closely with the required phosphorus load from the Task Group III results. The present results indicated that a Saginaw River phosphorus load of 485 mta, plus 97 mta from other inner bay sources, would lead to minimal compliance with the standard. This compared well with the value of 620 mta from the Task Group III results.

Results for annual average total phosphorus concentration were not as directly comparable because the TG results corresponded to the entire inner bay, and the present results corresponded only to segment two. It should be recalled that segment two contains 73 percent of the total water volume in the inner bay. The present results indicated that a phosphorus load of 462 mta from the Saginaw River, plus 97 mta from other inner bay sources would correspond to an annual average total phosphorus concentration of 15 µg/l in segment two. This compared with a value of 440 mta from the TG results to achieve the same concentration in the inner bay. The difference between results of the two studies was in the expected direction, and of approximately the expected magnitude, given differences in spatial segmentation and loading distribution. Annual average total phosphorus concentrations are somewhat higher for the inner bay than they are for segment two. That

TABLE X. COMPARISON BETWEEN RESULTS OF TASK GROUP III AND RESULTS OF PRESENT STUDY

Water Quality Objective	Total Phosphorus Load Required, metric tonnes per year	
	Task Group III	Present Study[1]
Minimal compliance with present taste and odor standard (T.O. = 3) for raw water at the Saginaw-Midland Water Filtration Plant intake at Whitestone Point	620[2]	485[3]
Maintain an annual average total phosphorus concentration of 15 µg/l in the inner bay	440[2]	462[3]

[1]Average of results relative to 1974 and 1975 conditions.
[2]Total load to inner bay.
[3]Saginaw River load. Other tributaries and atmosphere sources contribute an additional 97 mta directly to the inner bay.

is, a phosphorus load which would lead to a concentration of 15 µg/l for segment two, would lead to a somewhat higher concentration for the inner bay.

One of the water quality objectives considered by the TG in developing its final recommendation was to maintain an annual average total phosphorus concentration of 10 µg/l in the inner bay. The TG concluded that a phosphorus load of 210 mta would be required to achieve this objective. Subsequent to the TG recommendation of the 440 mta phosphorus loading objective, the IJC (March, 1980) considered the 210 mta loading objective, but noted that the large diffuse source reductions required were impractical. The present results indicated that a phosphorus load of 210 mta for the Saginaw River, plus 97 mta from other inner bay sources, corresponded to an annual average total phosphorus concentration of 13.6 µg/l in segment two. This was the average between 1974 and 1975 conditions. The corresponding inner bay concentration would be somewhat higher. The results imply that to achieve an annual average total phosphorus concentration of 10 µg/l in the inner bay, phosphorus loads must be reduced below 210 mta for the Saginaw River and/or the additional 97 mta from non-Saginaw River sources must be reduced.

CONCLUSIONS

The final calibration results for the phytoplankton model compared favorably with comprehensive sets of field data for 1974 and 1975 on Saginaw Bay. On the basis of a statistical analysis, model output for 13 principal variables described the Saginaw Bay system approximately 86 percent as well as the actual data for these 13 variables.

It was found that conditions in segment two were most closely related to the water quality issues on Saginaw Bay. Segment two contains 73 percent of the total water volume in the inner portion of the bay.

The 1978 WQA phosphorus loading objective for Saginaw Bay was 440 mta. Results of phosphorus load reduction simulations indicated that for a Saginaw River load of 440 mta, annual average total phosphorus concentration in segment two decreased to 14.8 µg/l. This value was the average of results relative to 1974 and 1975 conditions, and it represented an average reduction of 26 percent relative to the calibration results. At this same phosphorus load, results indicated that peak blue-green biomass concentrations decreased to 1.01 mg dry wt/liter. This value represented an average reduction of 63 percent relative to the calibration results.

Measured blue-green biomass concentrations in segment two were found to be significantly correlated with measurements for threshold odor at the Saginaw-Midland Water Supply intake at Whitestone Point. Water from this intake constitutes approximately 85 percent of all the water drawn from

Saginaw Bay for human use. Results indicated that for a Saginaw River phosphorus load of 440 mta, no violations of the U.S. Public Health Service standard for threshold odor would occur in the water supply.

In conclusion, results of the present study were in close agreement with results from Task Group III in terms of meeting the water quality objectives for Saginaw Bay. These results should serve to reinforce the scientific credibility, and to increase the degree of confidence in the accuracy of the 1978 WQA phosphorus loading objective for Saginaw Bay.

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APPENDIX A

Final Calibration Plots for 1974 and 1975 Conditions

The following plots are the final results of the model calibration for 1974 and 1975. The model output is displayed as the solid line, while the observed data is represented by the dots and error bars.

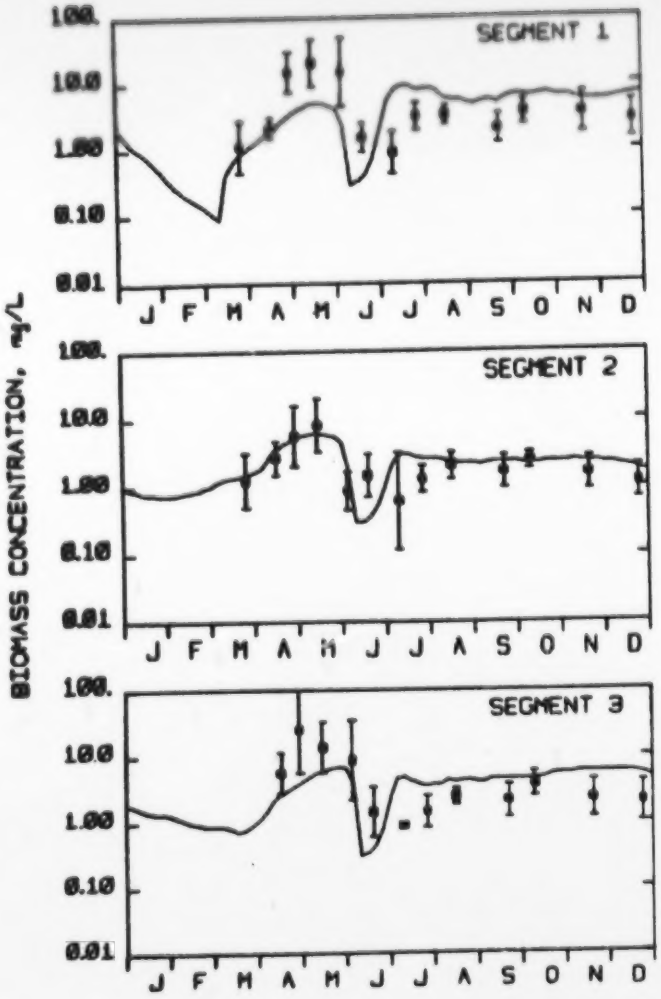
For the chemical variables, the dots correspond to the arithmetic mean of the observed data in a segment for a particular cruise. The error bars represent the mean plus or minus one standard deviation.

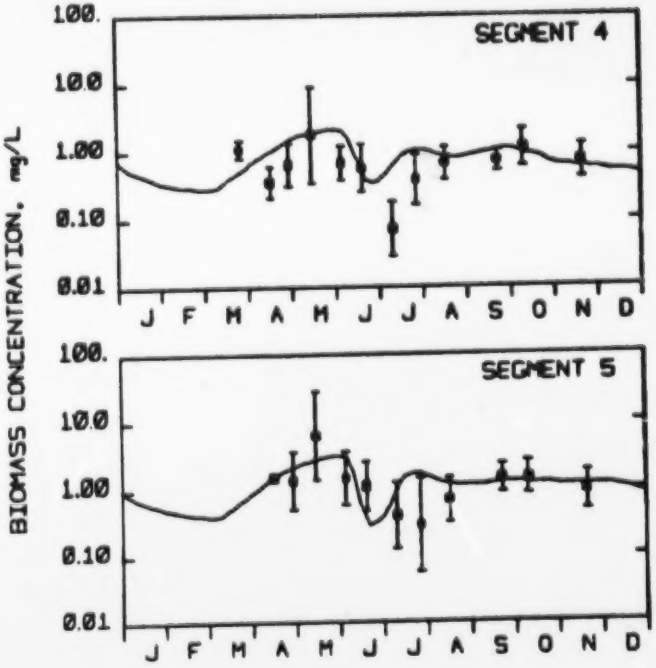
For the biological variables, the dots correspond to the maximum likelihood estimate of the mean of the observed data, assuming the data in a segment during a cruise is lognormally distributed. The maximum likelihood method used is given by Aitchison and Brown in "The Lognormal Distribution", Cambridge Press, 1963, p. 45. The error bars represent this mean multiplied or divided by the geometric standard deviation.

RUN 1

SAGINAW BAY 1974

TOTAL PHYTOPLANKTON

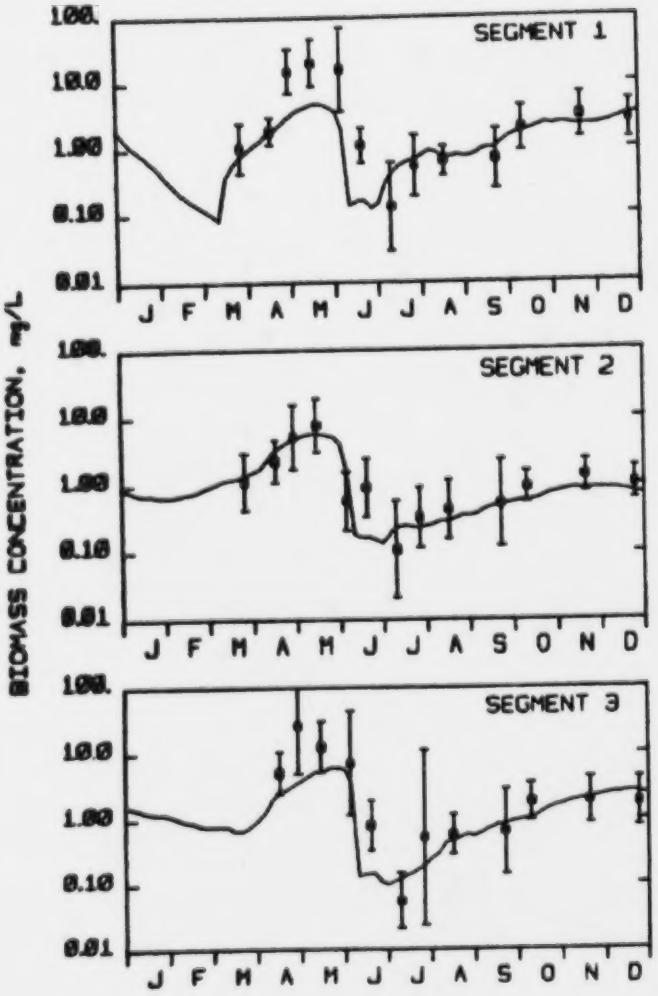


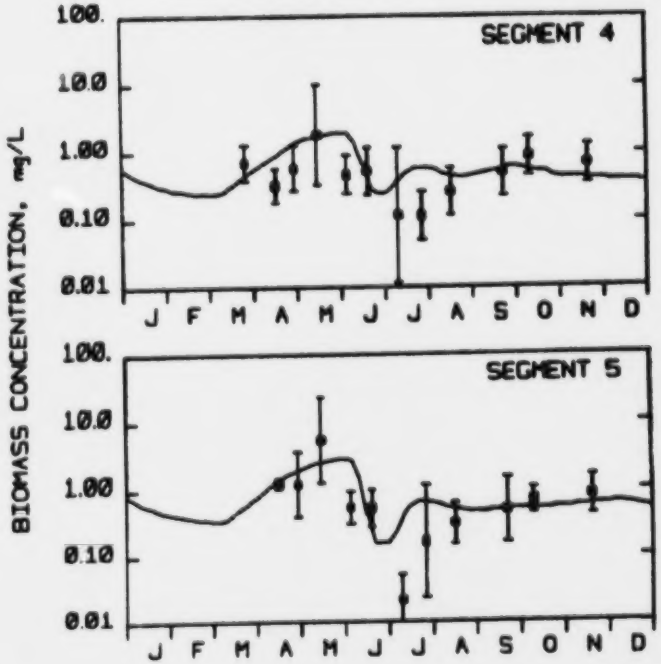


RUN 1

SAGINAW BAY 1974

DIATOMS

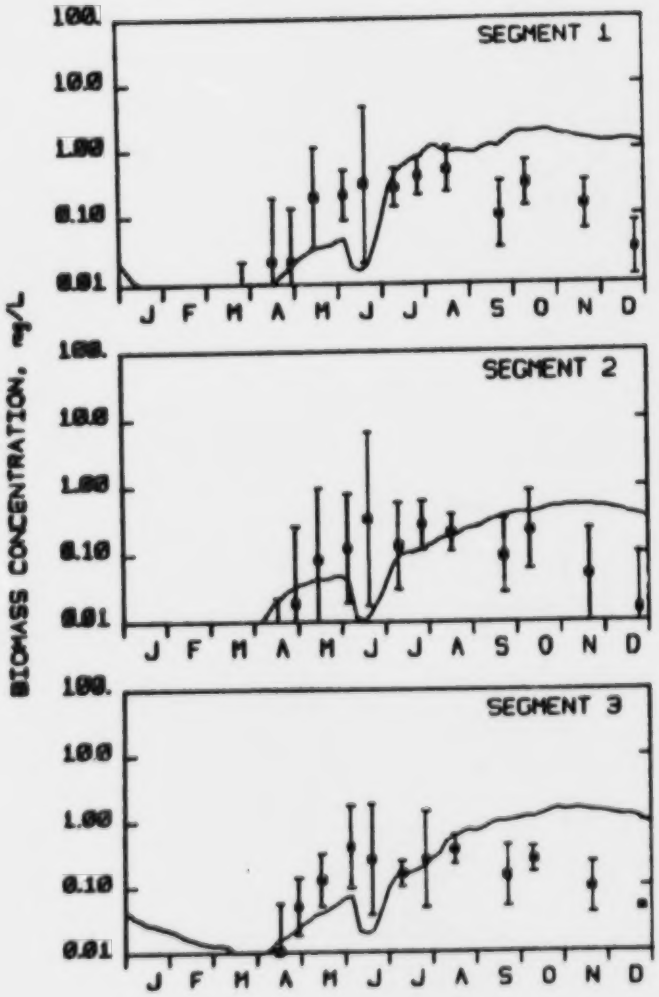


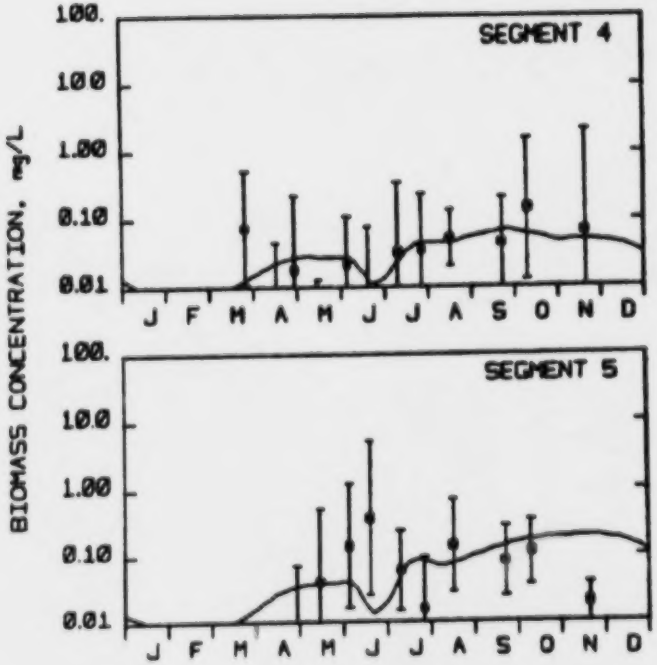


RUN 1

SAGINAW BAY 1974

GREENS

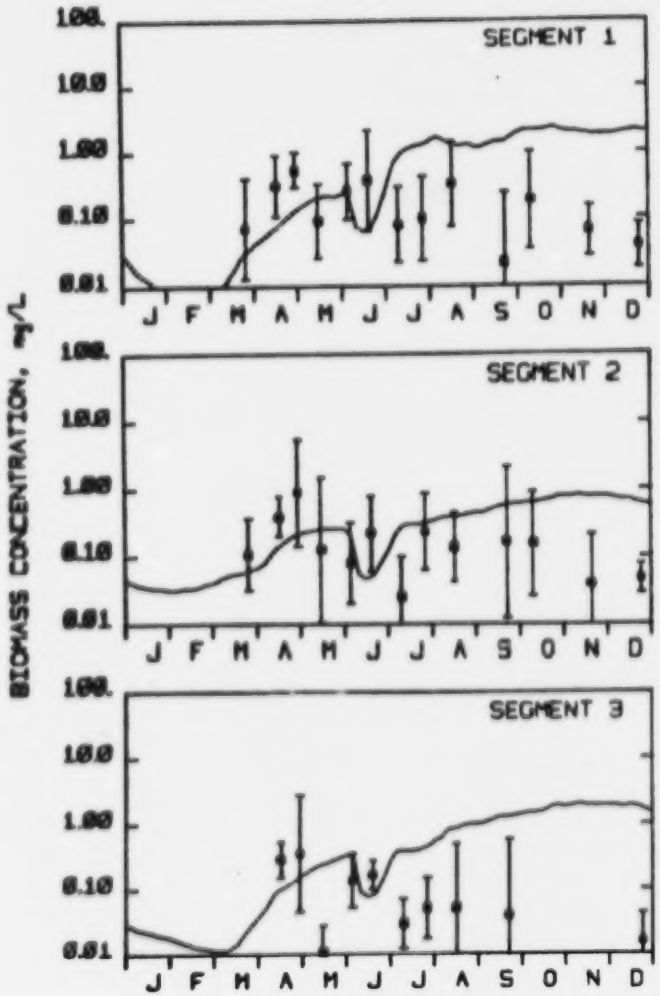


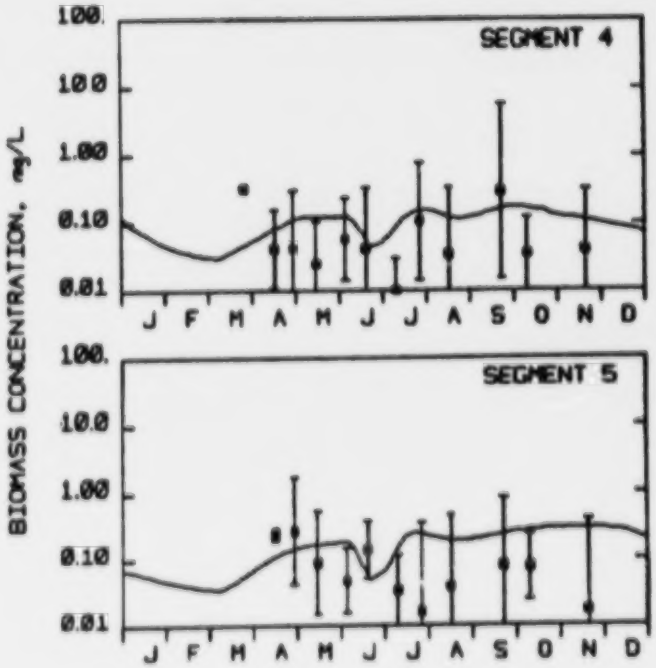


RUN 1

SAGINAW BAY 1974

OTHERS

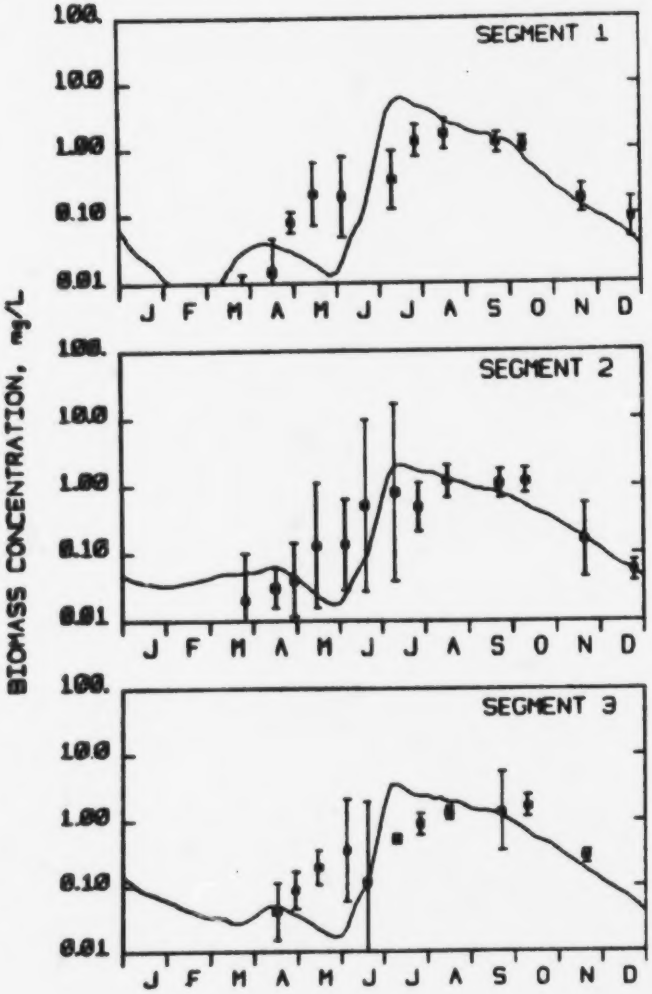


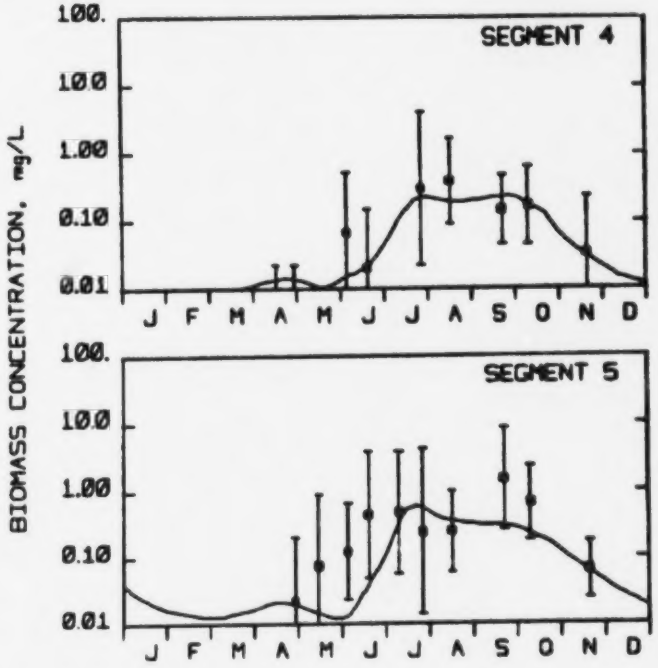


RUN 1

SAGINAW BAY 1974

BLUE-GREENS (NON-N2)

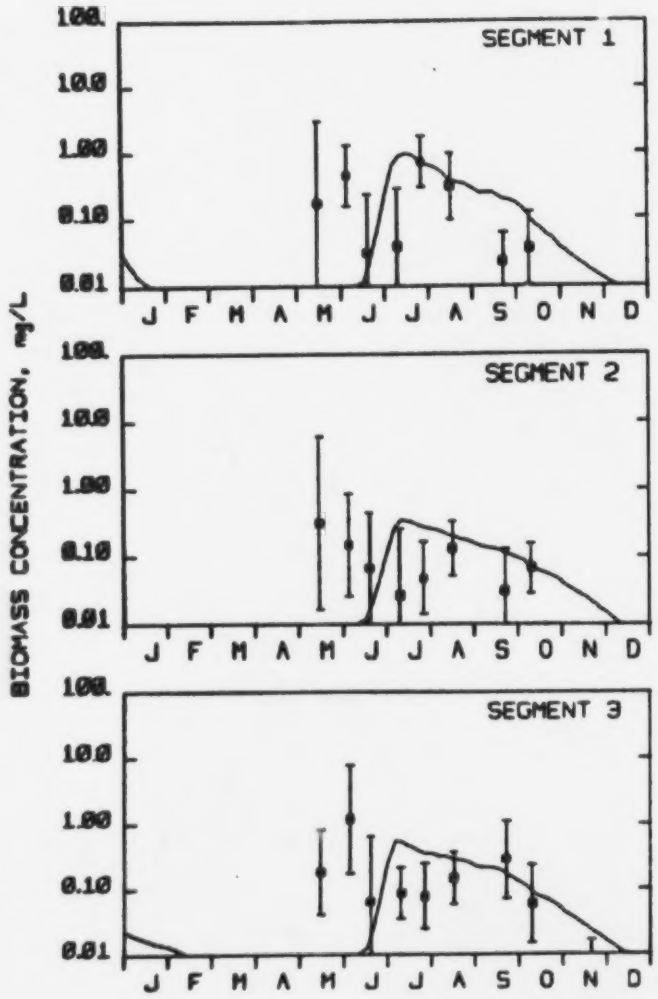


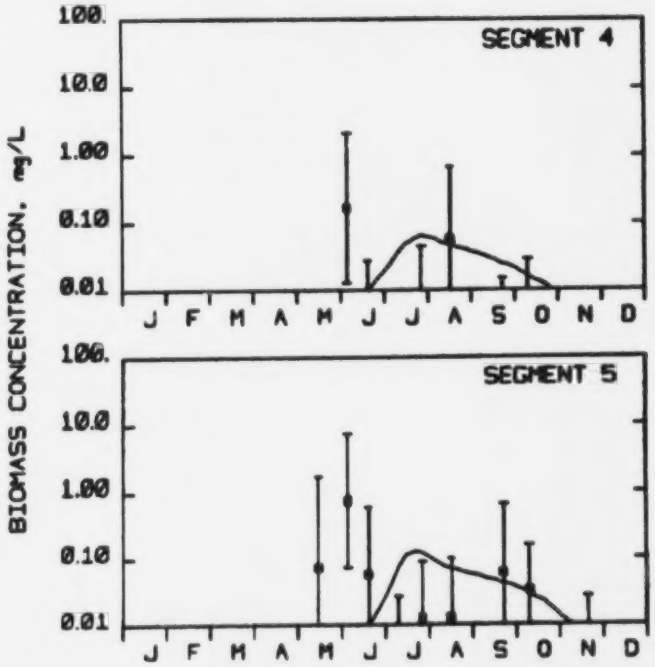


RUN 1

SAGINAW BAY 1974

BLUE-GREENS (N2)

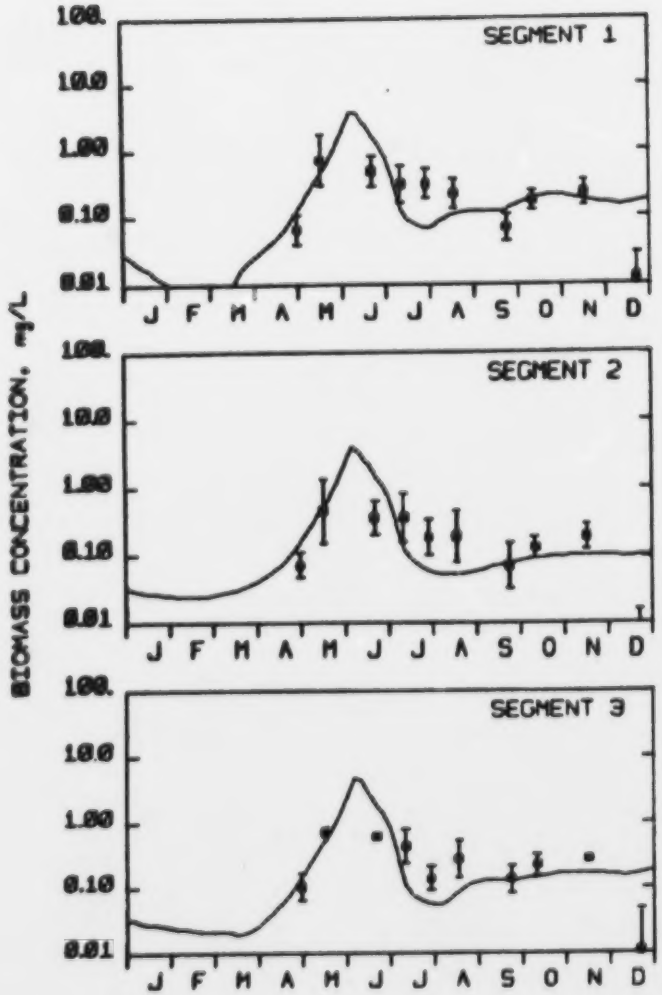


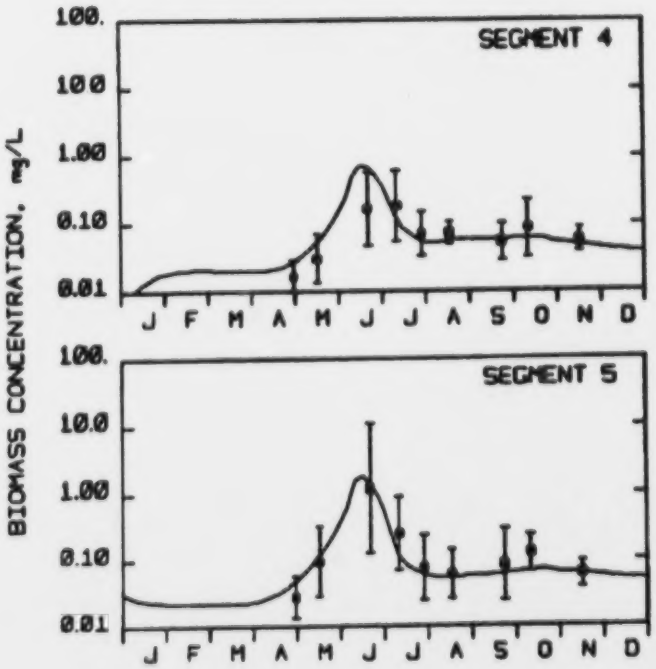


RUN 1

SAGINAW BAY 1974

TOTAL ZOOPLANKTON

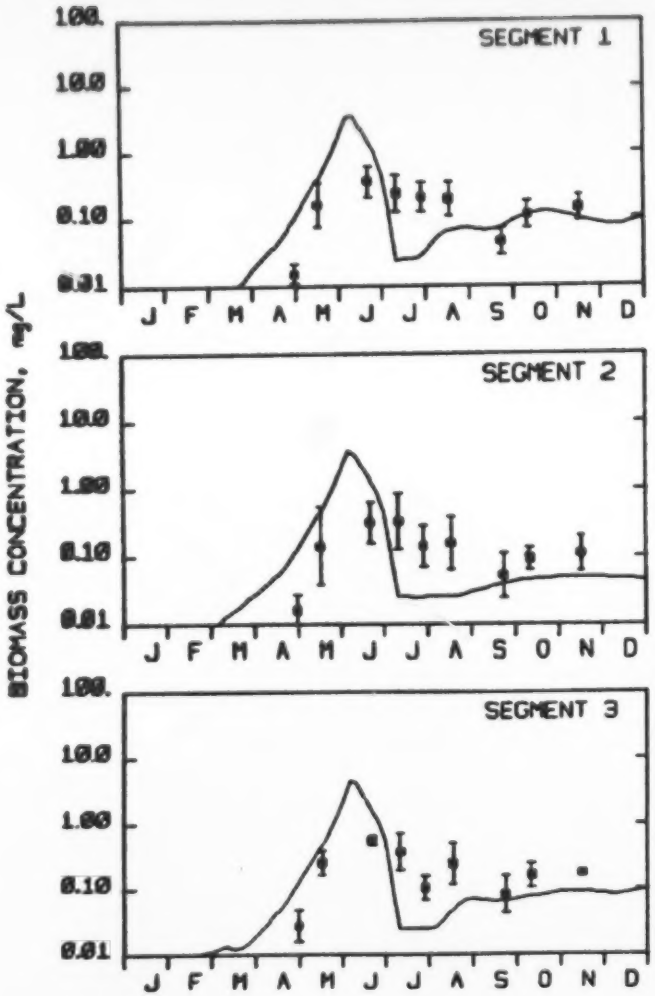


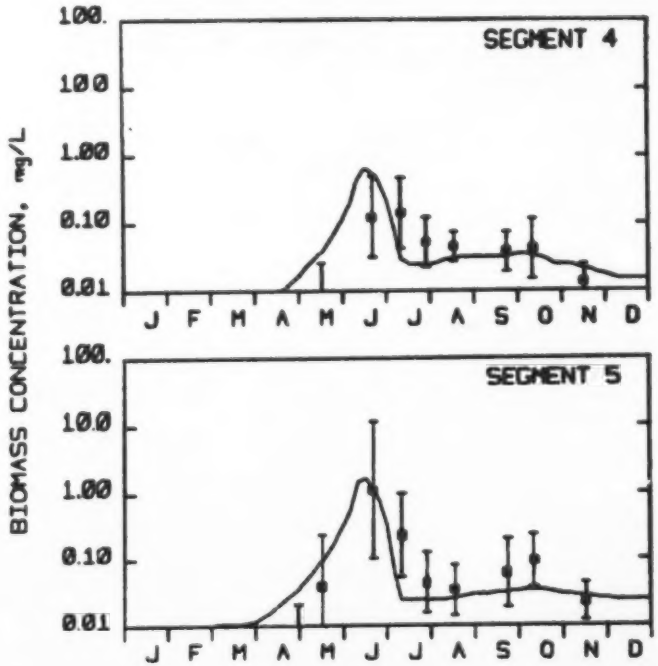


RUN 1

SAGINAW BAY 1974

HERBIVOROUS ZOOPLANKTON

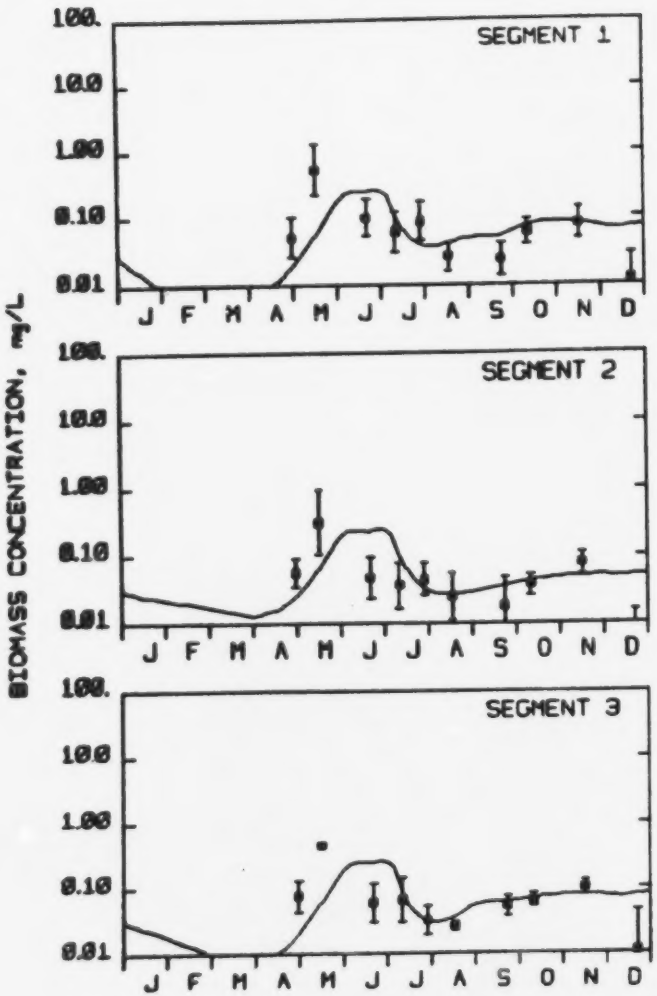


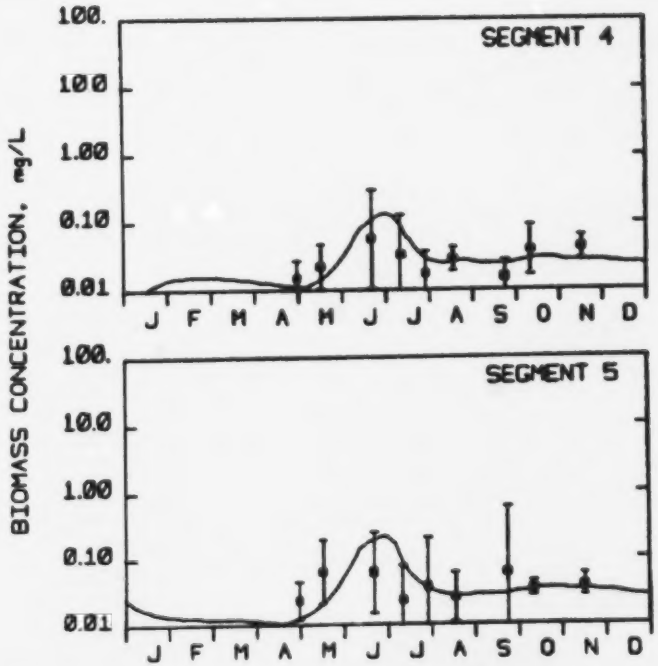


RUN 1

SAGINAW BAY 1974

CARNIVOROUS ZOOPLANKTON

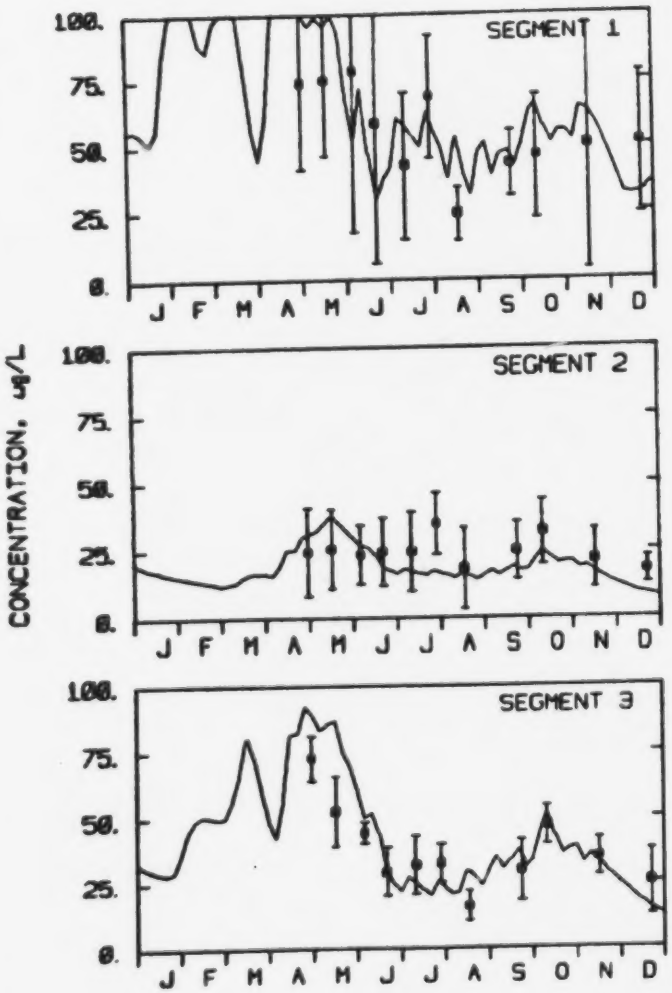


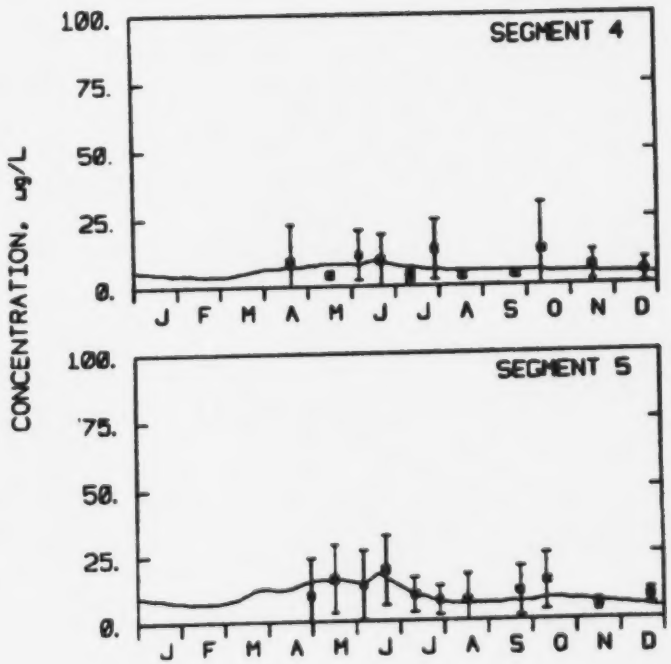


RUN 1

SAGINAW BAY 1974

TOTAL PHOSPHORUS

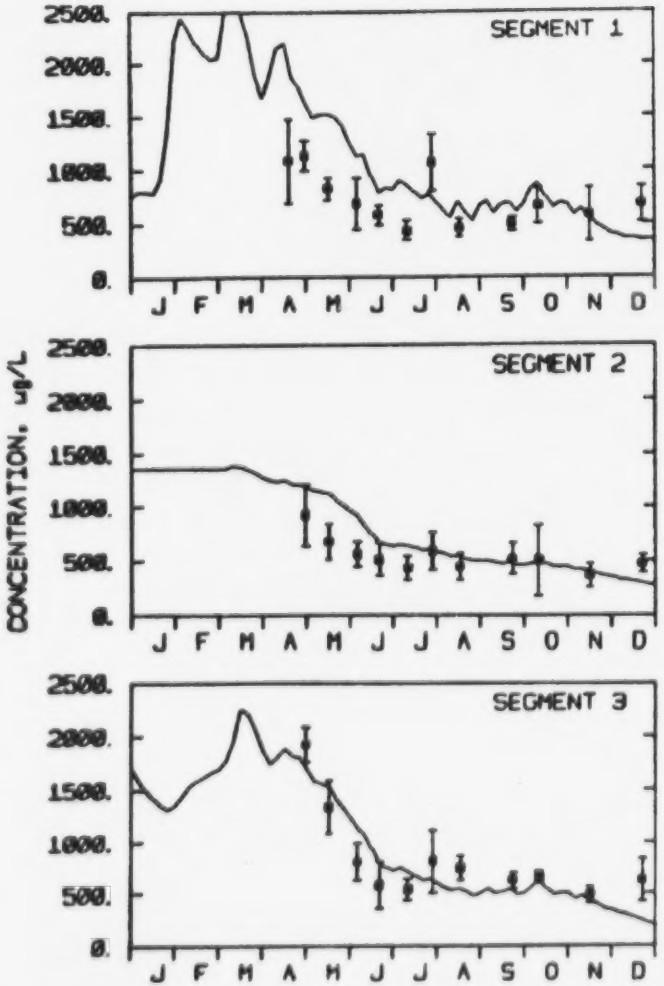


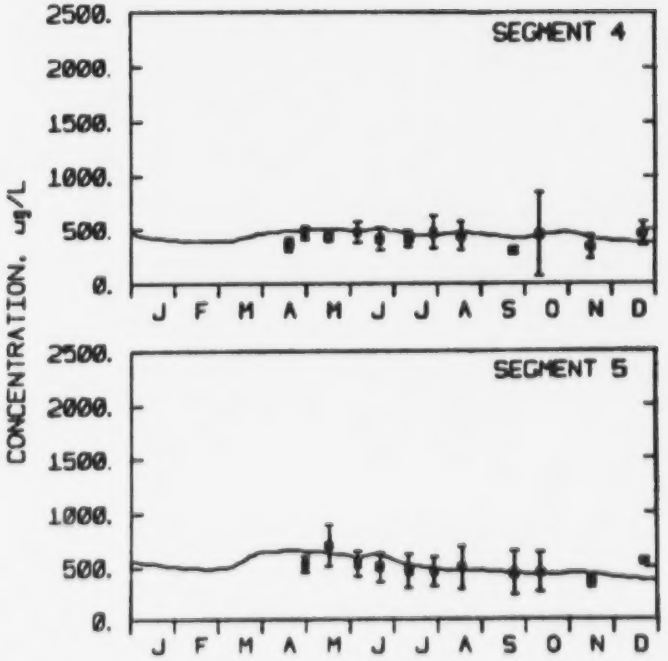


RUN 1

SAGINAW BAY 1974

TOTAL NITROGEN

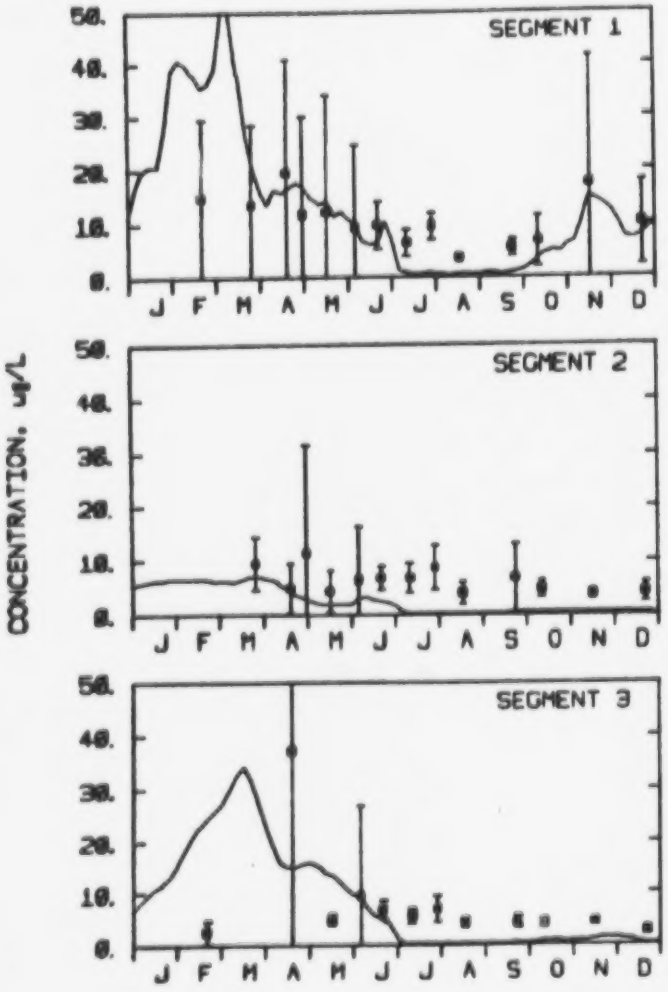


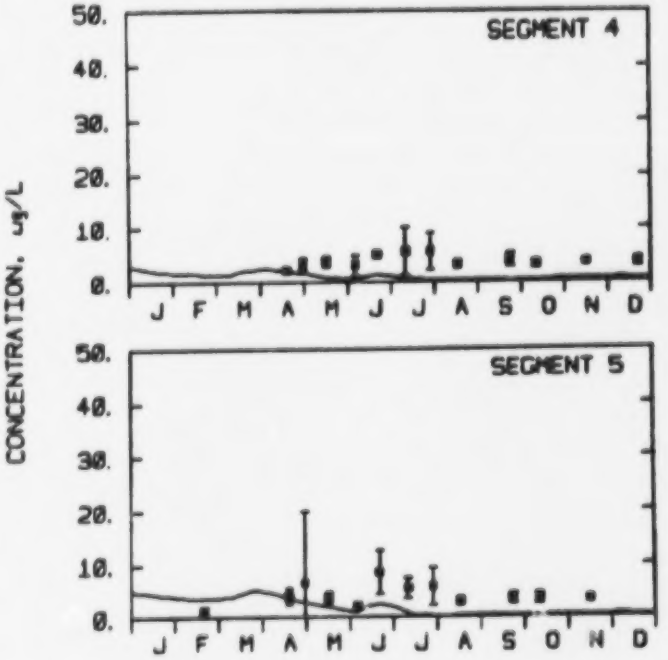


RUN 1

SAGINAW BAY 1974

DISSOLVED ORTHO-PHOSPHORUS

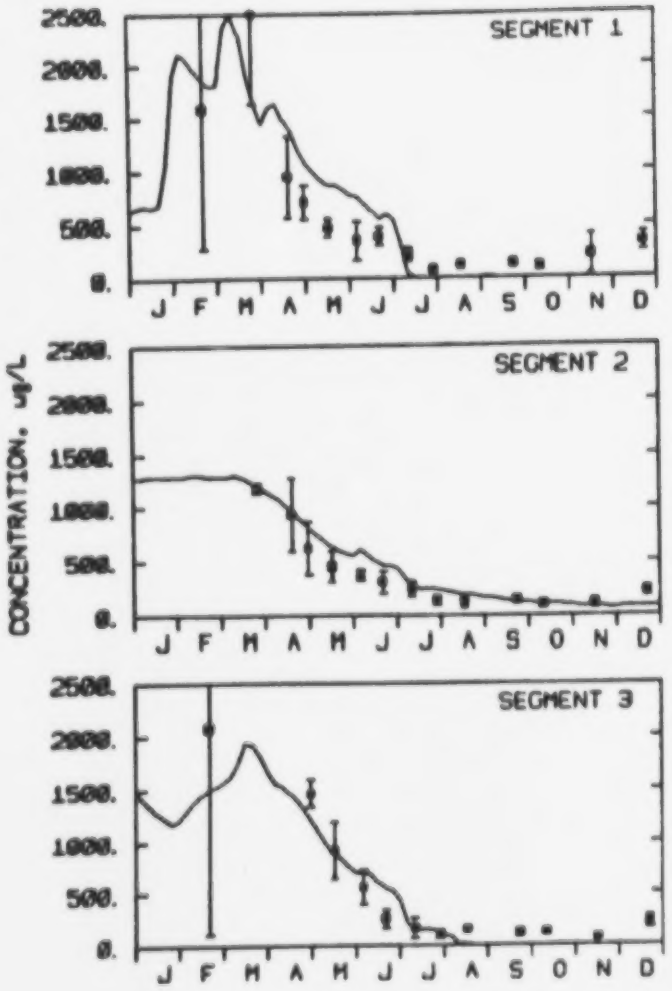


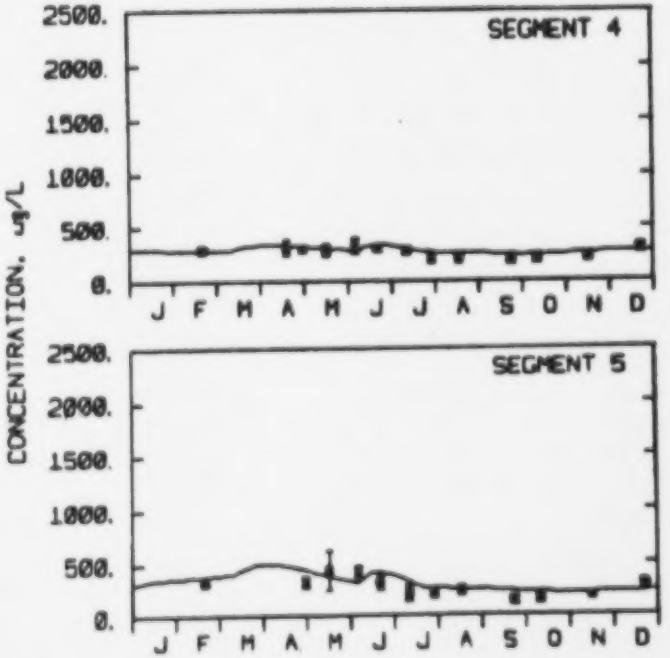


RUN 1

SAGINAW BAY 1974

DISSOLVED AVAILABLE NITROGEN

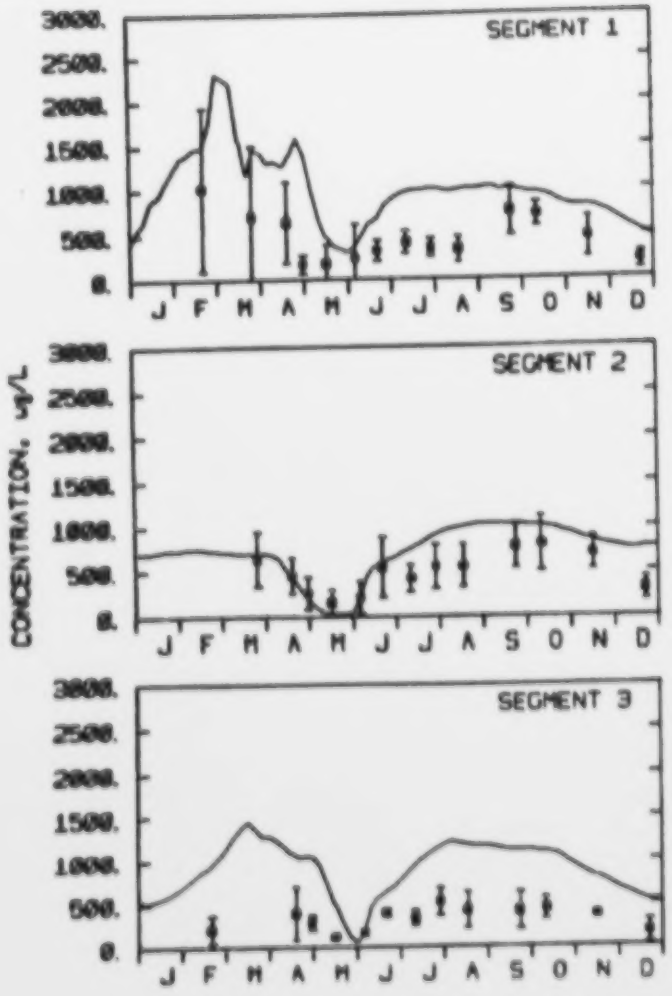


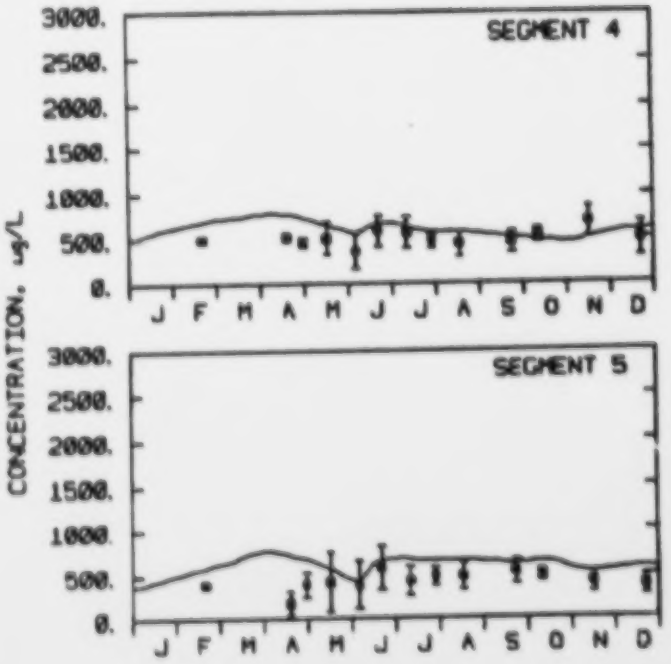


RUN 1

SAGINAW BAY 1974

DISSOLVED REACTIVE SILICON

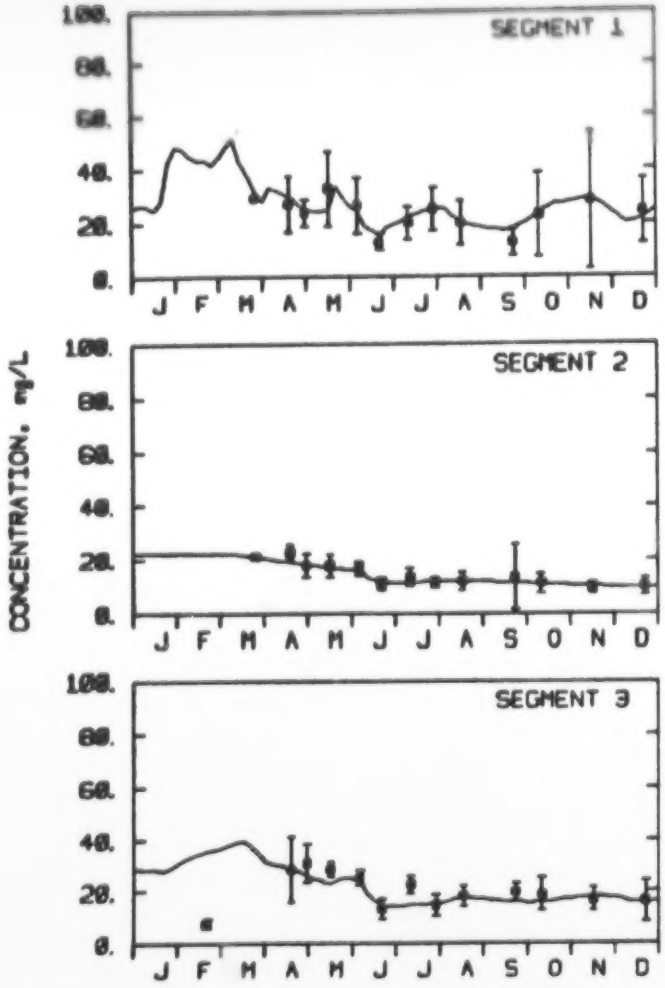


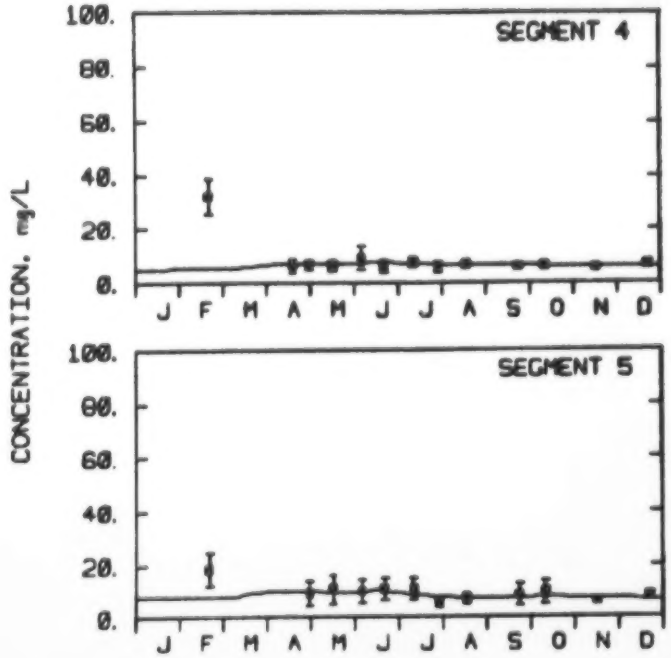


RUN 1

SAGINAW BAY 1974

CHLORIDE

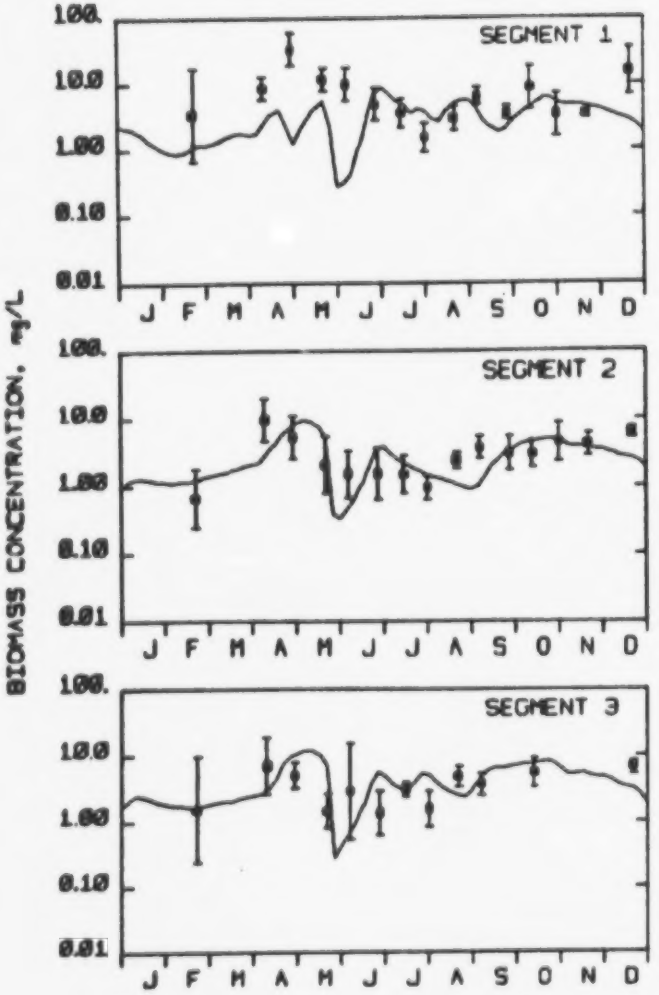


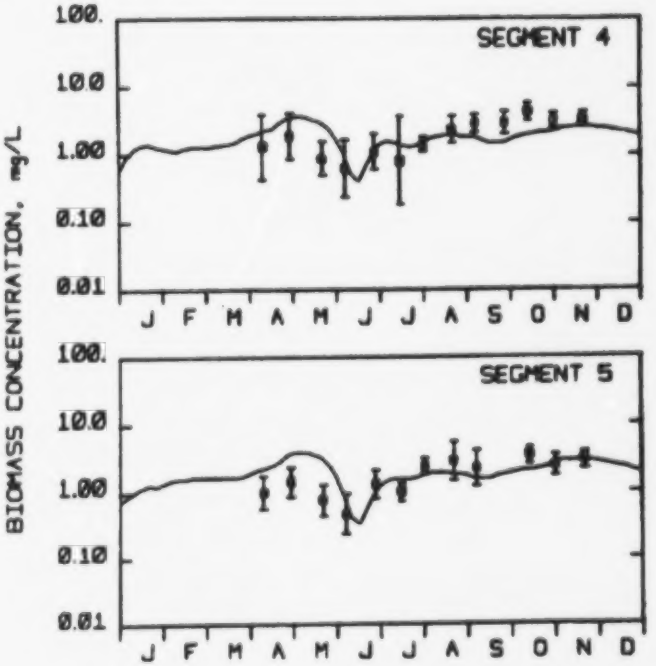


RUN 1

SAGINAW BAY 1975

TOTAL PHYTOPLANKTON

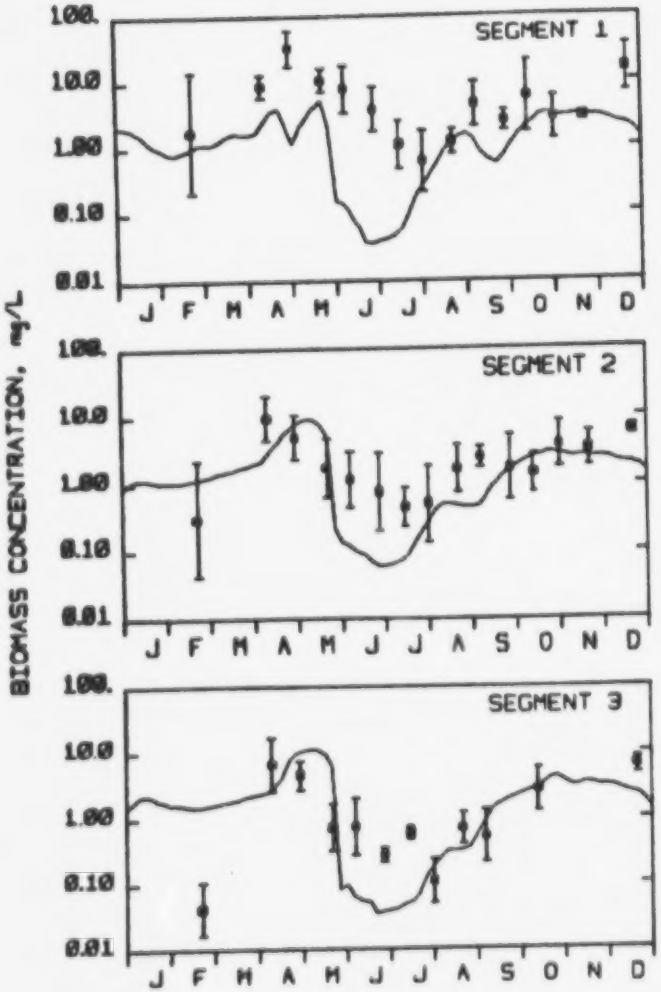


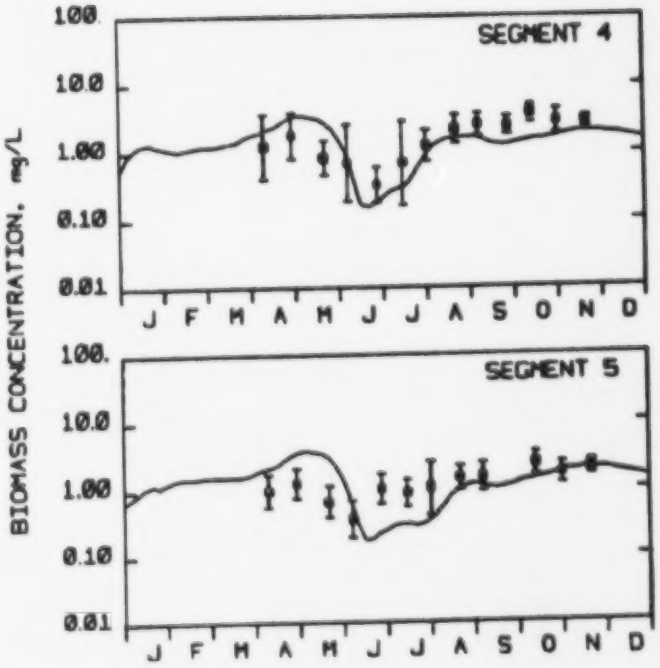


RUN 1

SAGINAW BAY 1975

DIATOMS

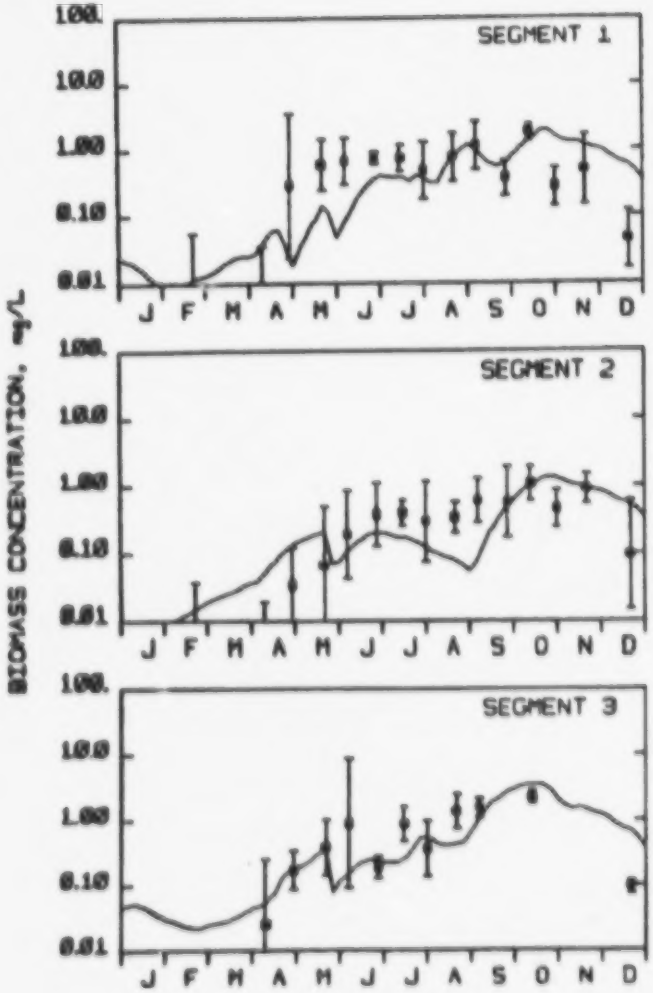


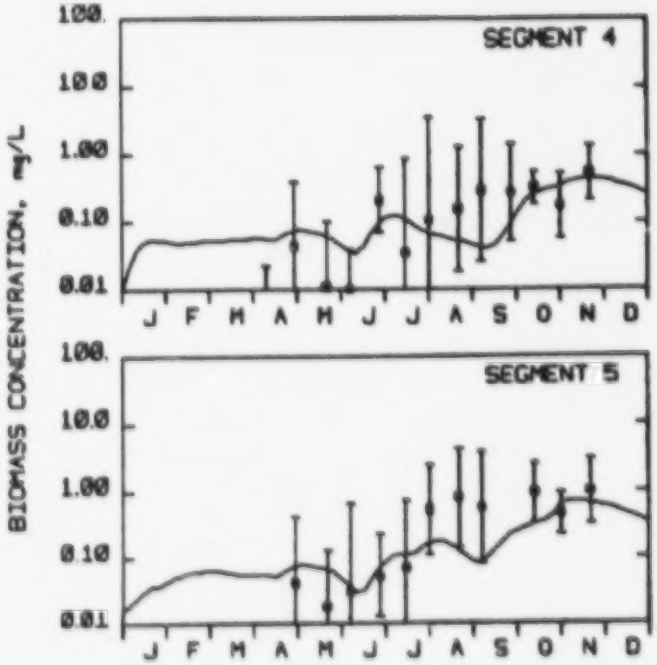


RUN 1

SAGINAW BAY 1975

GREENS

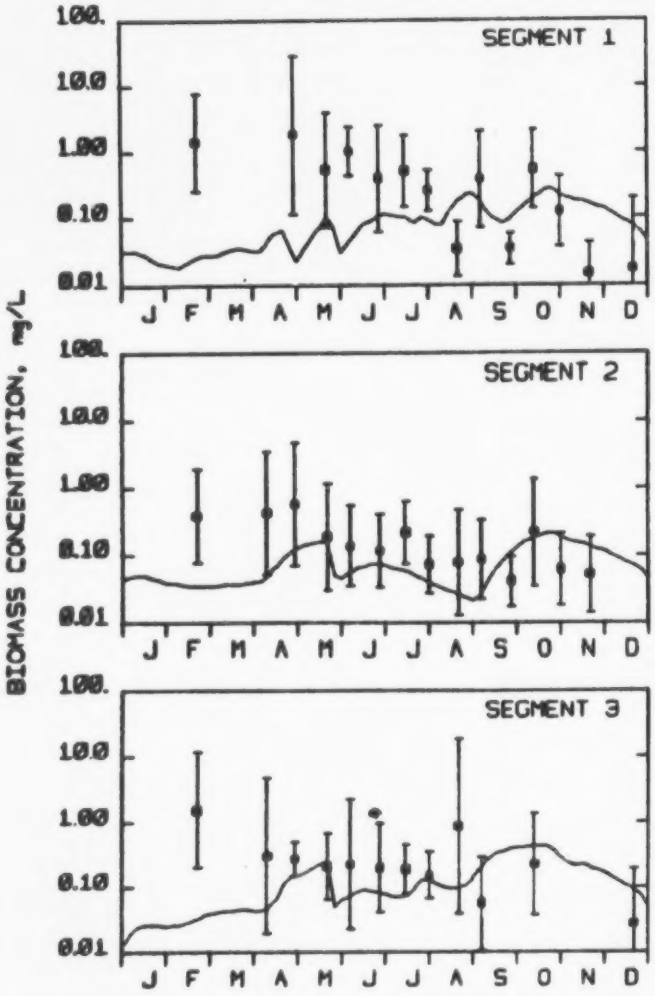


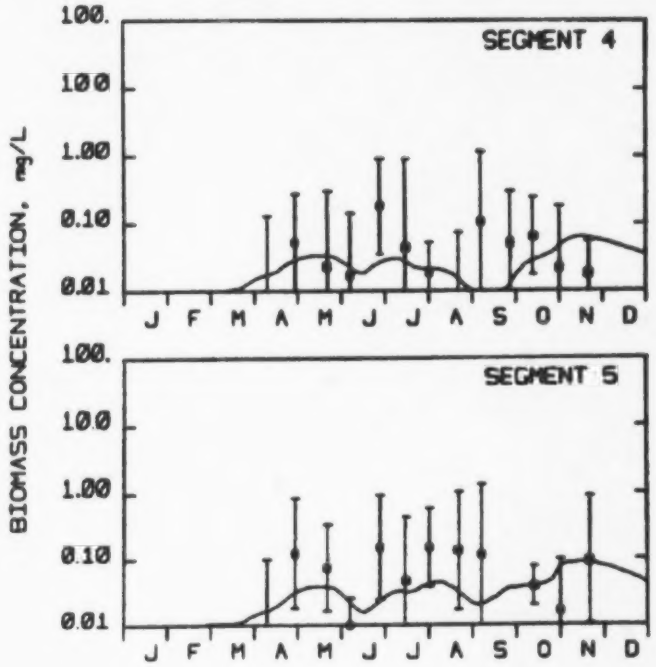


RUN 1

SAGINAW BAY 1975

OTHERS

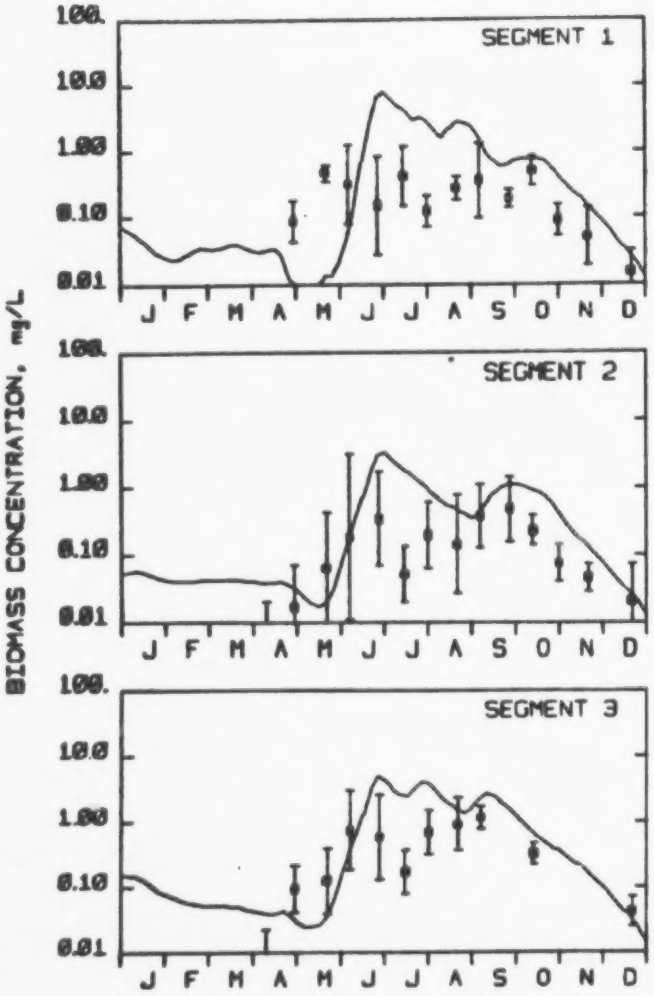


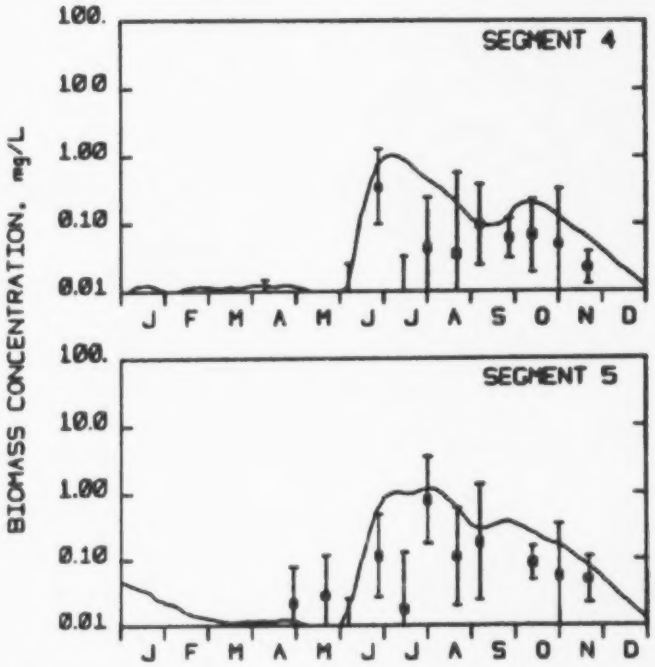


RUN 1

SAGINAW BAY 1975

BLUE-GREENS (NON-N2)

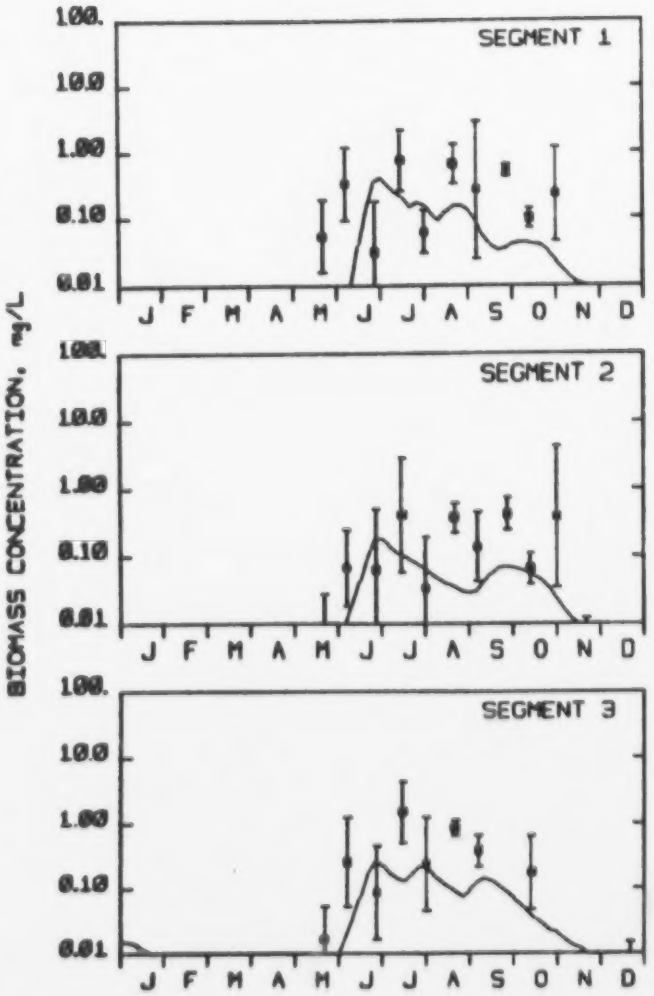


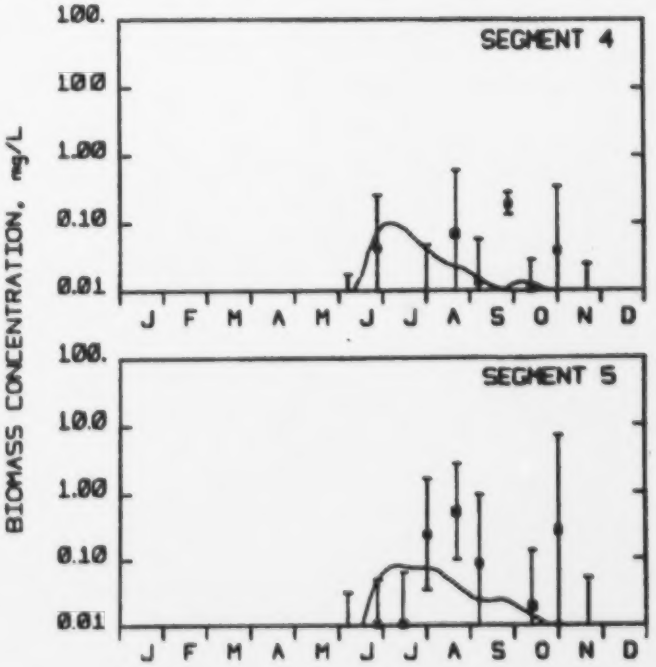


RUN 1

SAGINAW BAY 1975

BLUE-GREENS (N2)

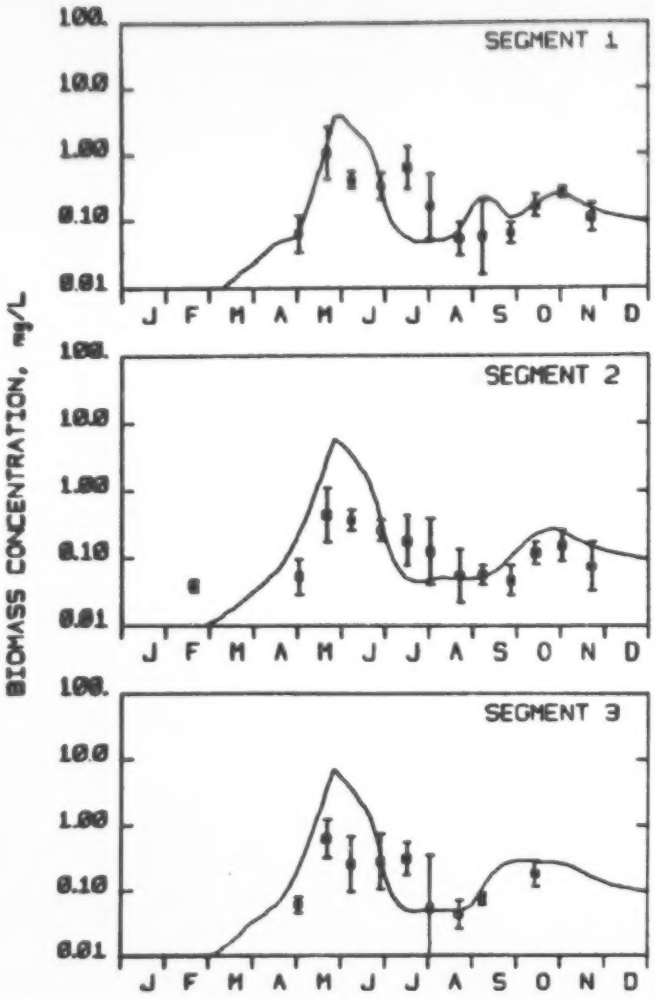


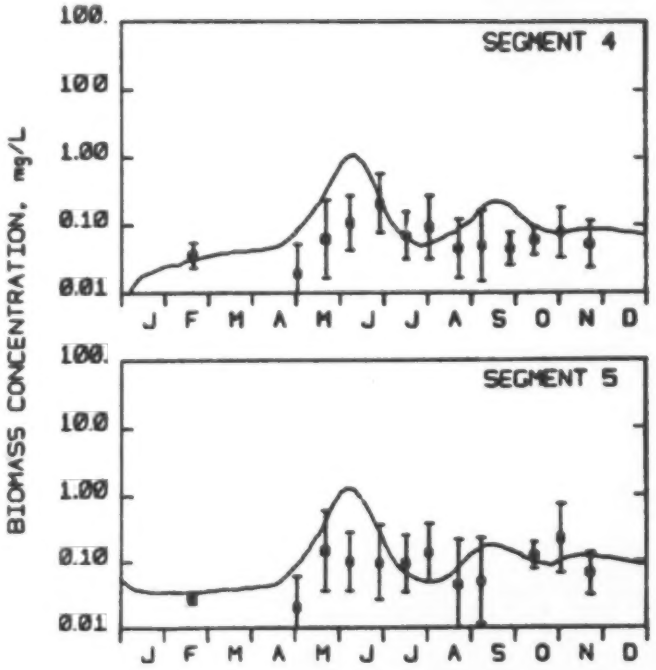


RUN 1

SAGINAW BAY 1975

TOTAL ZOOPLANKTON

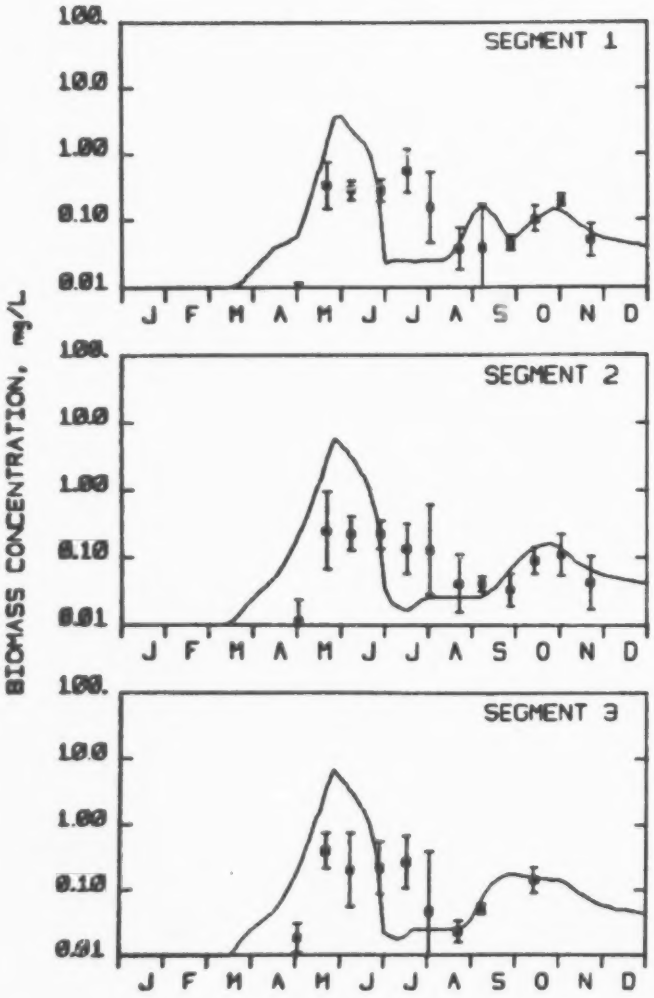


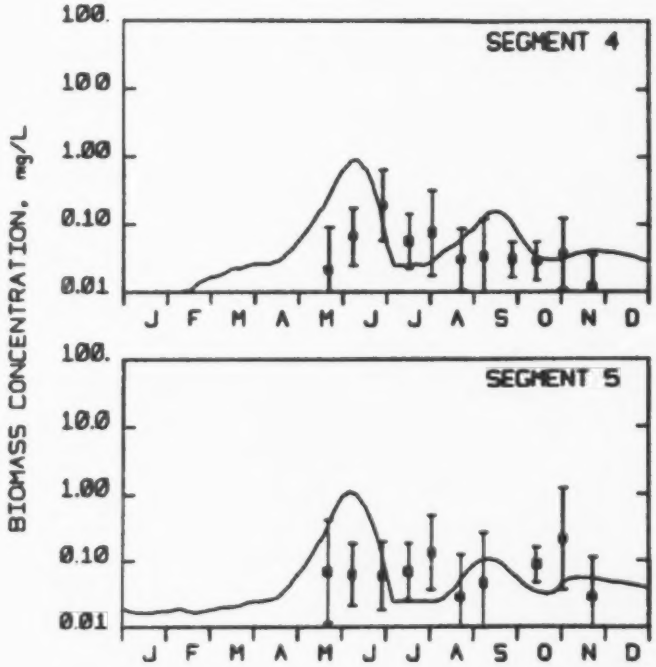


RUN 1

SAGINAW BAY 1975

HERBIVOROUS ZOOPLANKTON

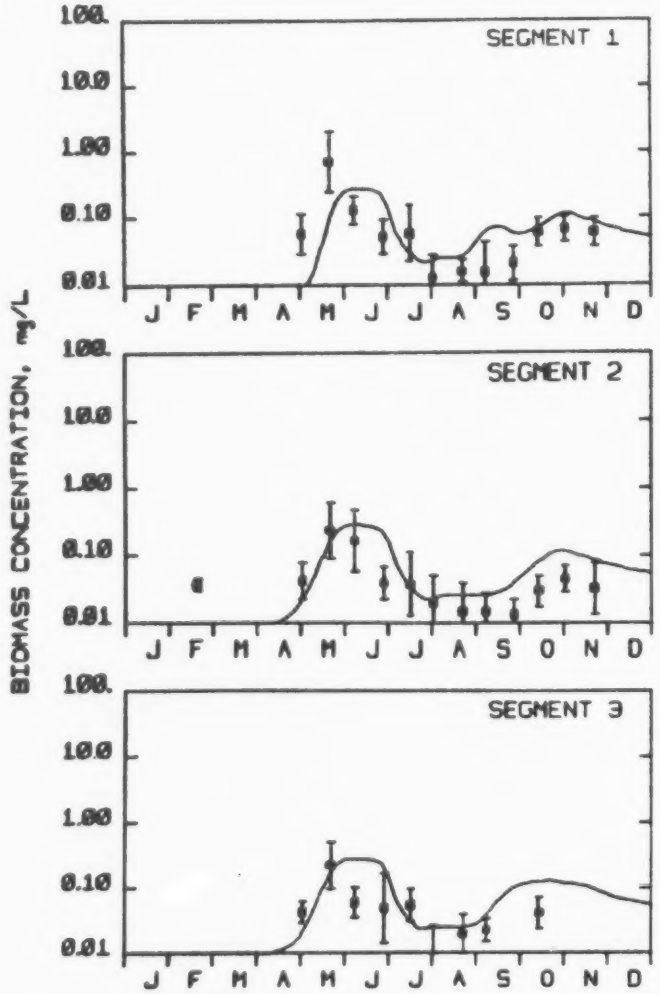


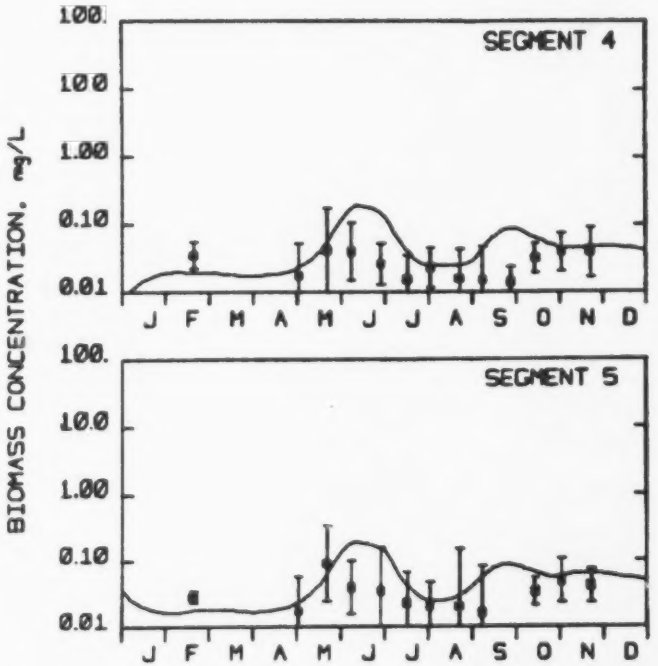


RUN 1

SAGINAW BAY 1975

CARNIVOROUS ZOOPLANKTON

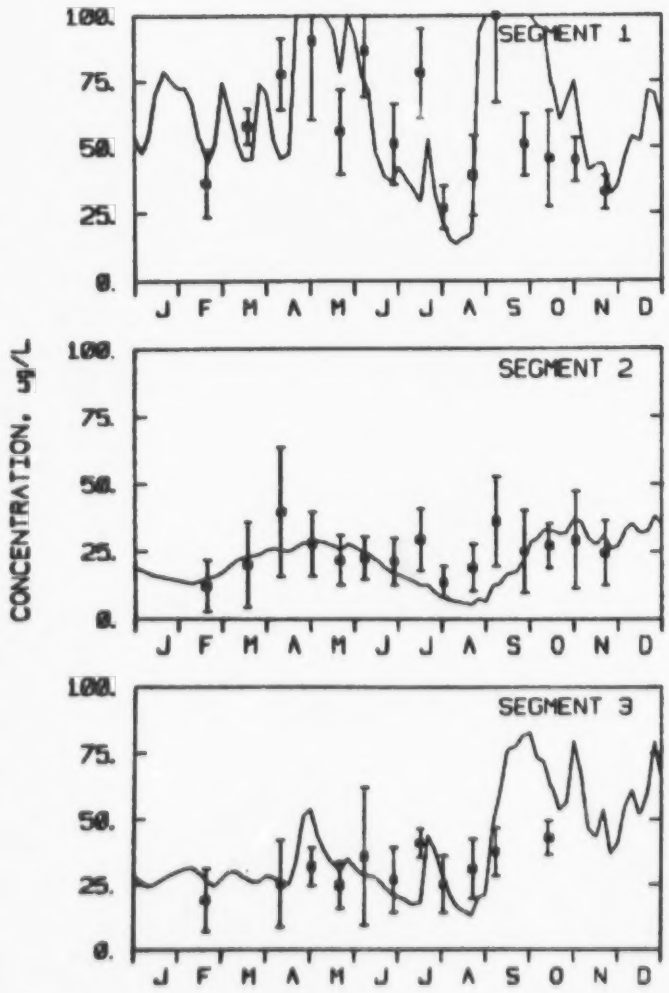


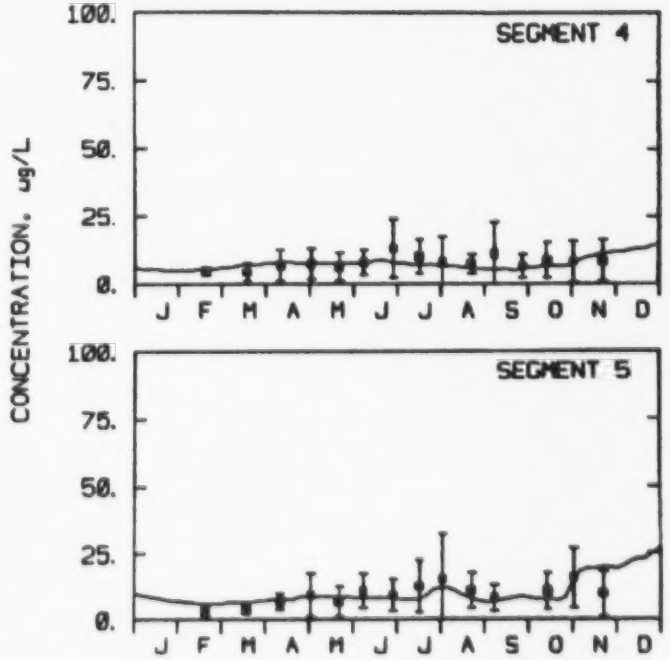


RUN 1

SAGINAW BAY 1975

TOTAL PHOSPHORUS

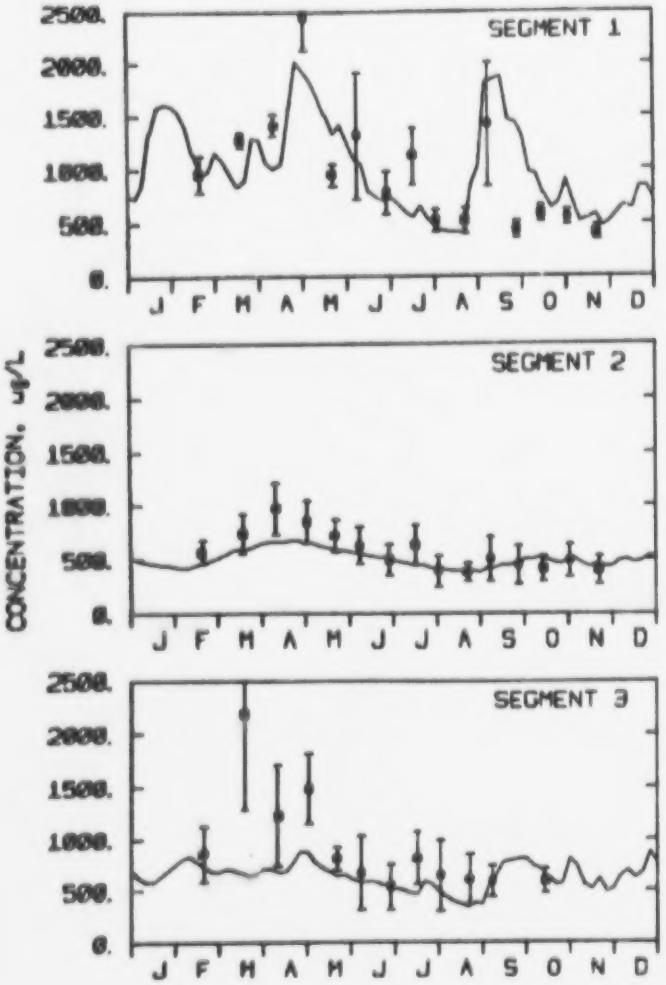


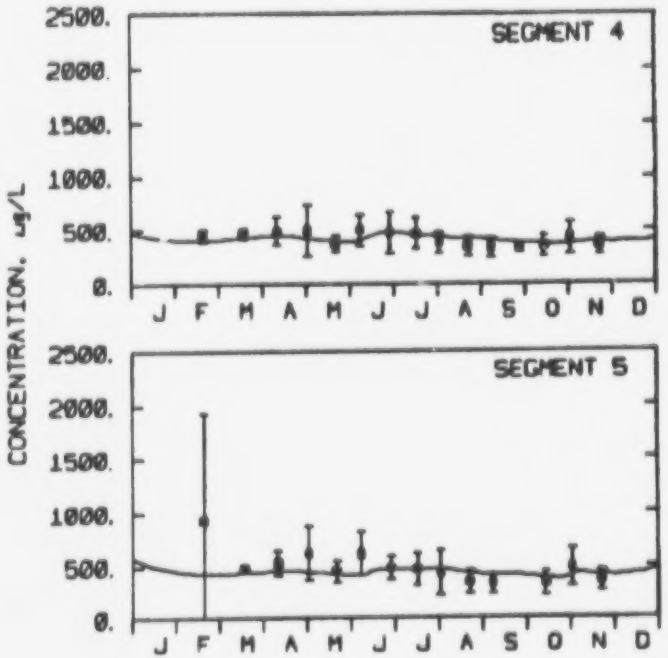


RUN 1

SAGINAW BAY 1975

TOTAL NITROGEN

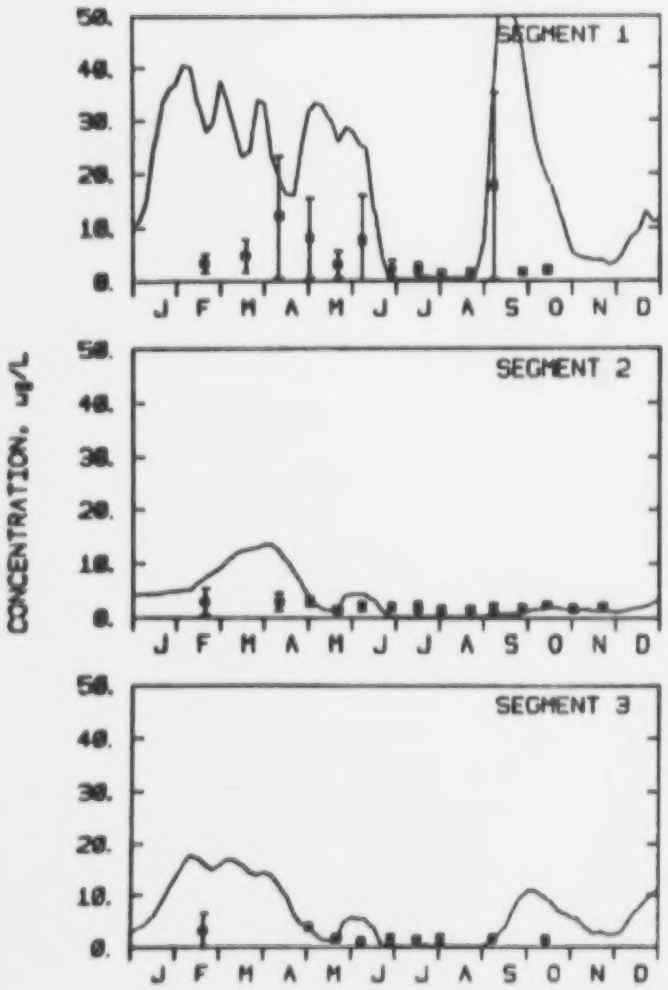


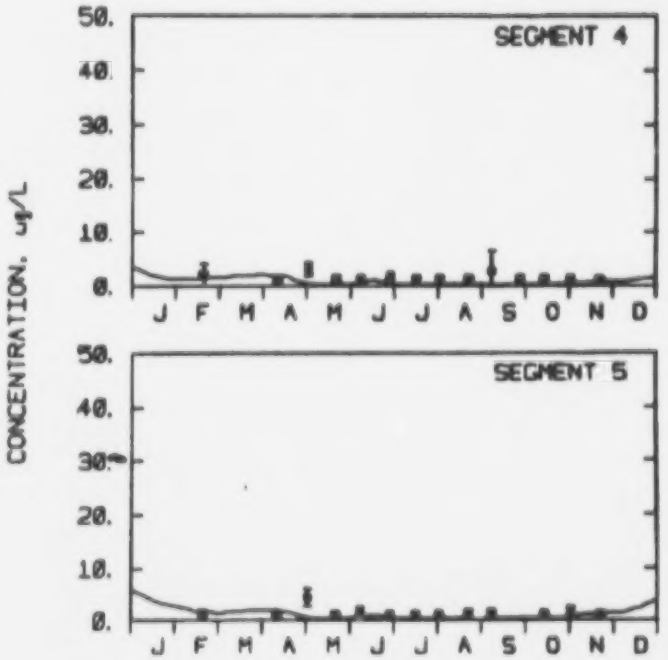


RUN 1

SAGINAW BAY 1975

DISSOLVED ORTHO-PHOSPHORUS

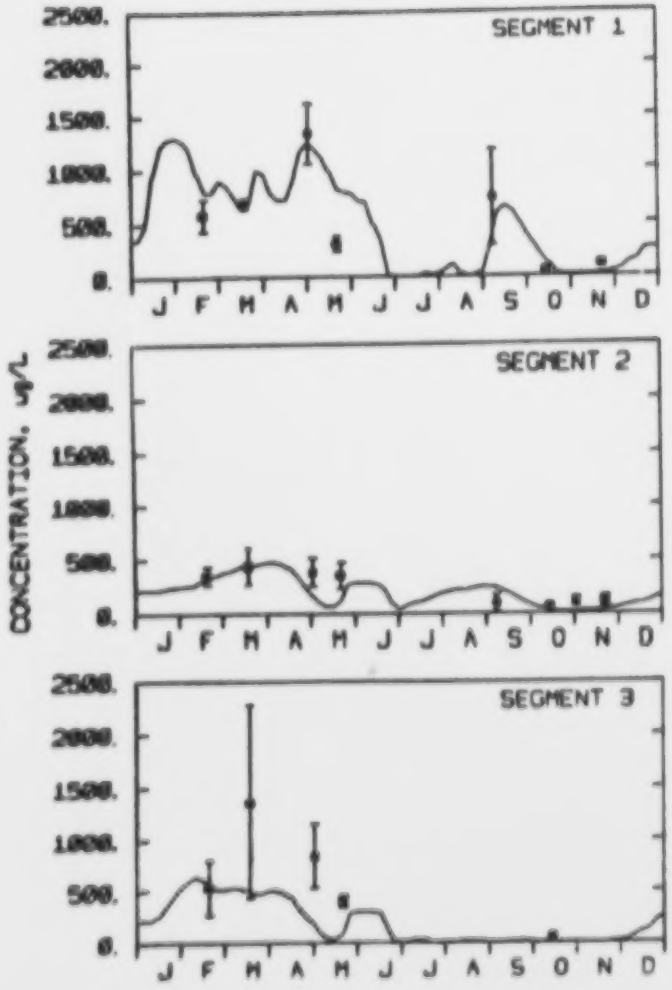


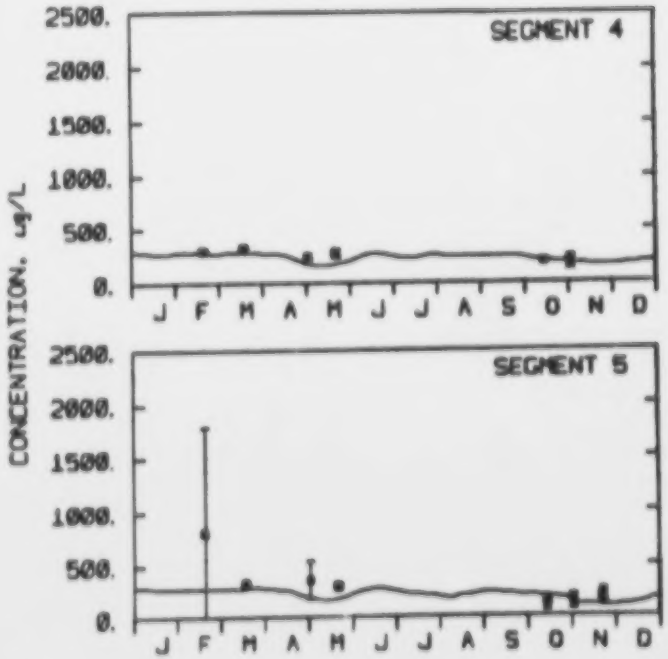


RUN 1

SAGINAW BAY 1975

DISSOLVED AVAILABLE NITROGEN

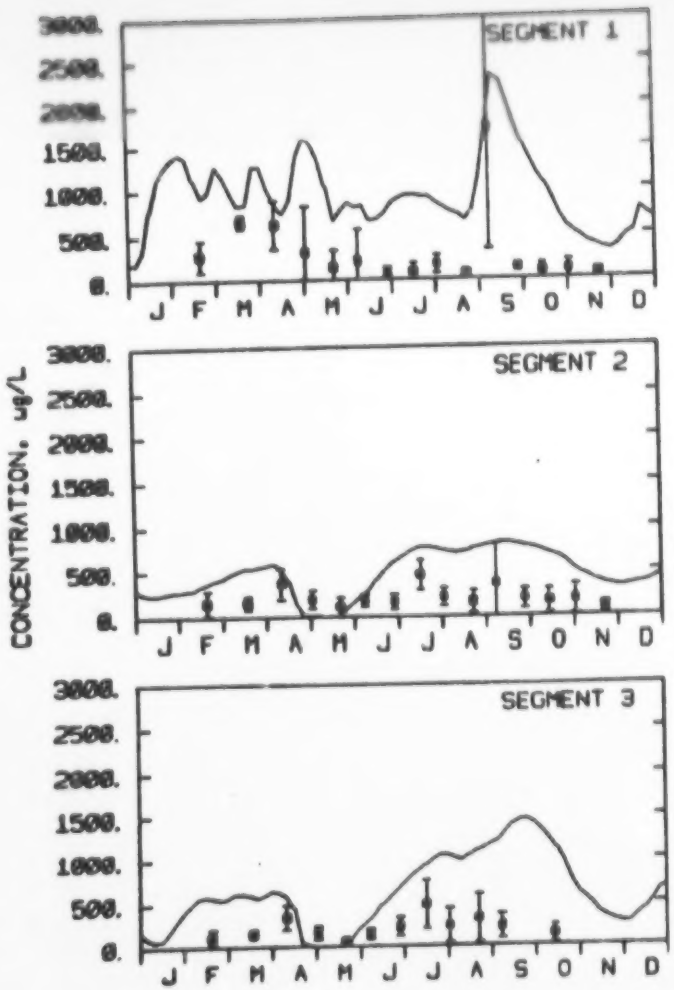


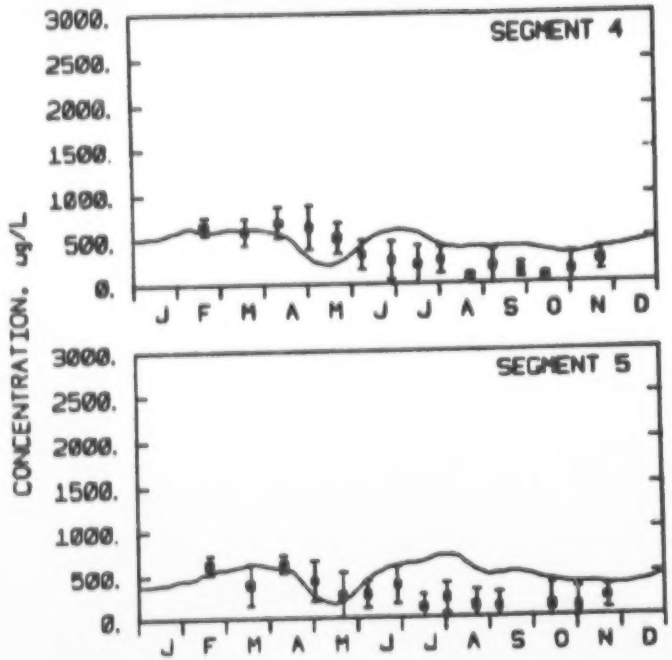


RUN 1

SAGINAW BAY 1975

DISSOLVED REACTIVE SILICON





RUN 1

SAGINAW BAY 1975

CHLORIDE